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THE EFFECTS OF HEAT EXCHANGE AND THERMAL ADVECTION ON THE RATE OF CHANGE OF TEMPERATURE AT OCEAN WEATHER STATION NOVEMBER

Larry Martin Thorne

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THESIS

THE EFFECTS OF HEAT EXCHANGE AND THERMAL ADVECTION
ON THE RATE OF CHANGE OF TEMPERATURE
AT OCEAN WEATHER STATION NOVEMBER

by

Larry Martin Thorne

September 1974

Thesis Advisor: R. H. Bourke

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20. Abstract continued--

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The Effects of Heat Exchange and Thermal Advection on the Rate of Change of Temperature at Ocean Weather Station November

by

Larry Martin Thorne
Lieutenant, United States Navy
B. S., University of Montana, 1966

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
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I. INTRODUCTION

Of vital concern to ocean studies today are the factors, or forces, which change the near surface operating environment. Since most of the driving forces are atmospheric in origin, many studies have been made as to how these forces may be used to predict the change in such ocean variables as temperature, currents, and heat exchange. A knowledge of the changes in these variables observed in certain conditions is extremely important to Naval Anti-Submarine Warfare Operations and in fishery problems, for example.

Air-sea interaction involves a transfer of atmospheric momentum and heat across the sea surface. Momentum transfer leads to turbulence which affects the depth of the mixed layer. The heat exchange also affects the layer depth through surface cooling which by convective overturning results in a deepening of the layer depth and through heating which leads to shallower layers. Both of these processes of interaction contribute to the thermal structure of the seas.

The sea surface temperature (SST) is one of the most commonly measured and truly oceanographic elements reported in synoptic marine weather reports [Carstensen and Wolff, 1966]. Changes in the SST are indicative of changes in other environmental elements. SST is influenced by many environmental factors, but the most important are heat exchange, mixing, and advection [Laevastu and Hubert, 1970]. The dominance by one or more of these processes depends upon the season of the year and ocean region.

An influential process in the alteration of the thermal structure at the air-sea interface is insolation. Insolation is the addition of

heat to the ocean by absorption of shortwave radiation. The incoming insolation combined with effective back radiation, evaporation, condensation, and sensible heat conduction acts to produce absolute heat changes [James, 1966]. Insolation tends to produce negative temperature gradients; whereas, removal of heat from the ocean eliminates negative gradients and produces slightly positive gradients [LaFond, 1954].

Mixing and advection produce vertical and horizontal temperature gradients by movement of water below the sea surface. The vertical and horizontal temperature gradients will change if the temperature of the advected water is different from the displaced water [LaFond, 1954]. Advection as defined by James [1966, p. 18] is "...the transport of a property solely by the velocity field and as the rate of change of an advected property at a point." The computation of advection comes from a knowledge of the temperature gradient and the ocean current field.

The vertical temperature gradient is primarily determined by mixing processes. The redistribution of heat by mixing processes occurs in two ways--convective mixing and mechanical mixing [Beland, 1971]. Convective mixing (predominant in the winter) occurs when there is a heat loss from the ocean. The result is a cooling of the surface water and a subsequent sinking of that water. Mechanical mixing results from wave motion and the action of the wind. The effect of mechanical mixing is the development of an isothermal upper layer that has a sharp underlying thermocline [James, 1966]. The effect of mechanical mixing on temperature structure is particularly noticeable in the summer.

The effect of thermal advection and heat exchange on the thermal structure at Ocean Weather Station (OWS) NOVEMBER (Figure 1) is the purpose of this study. Recent studies at OWS NOVEMBER have examined the

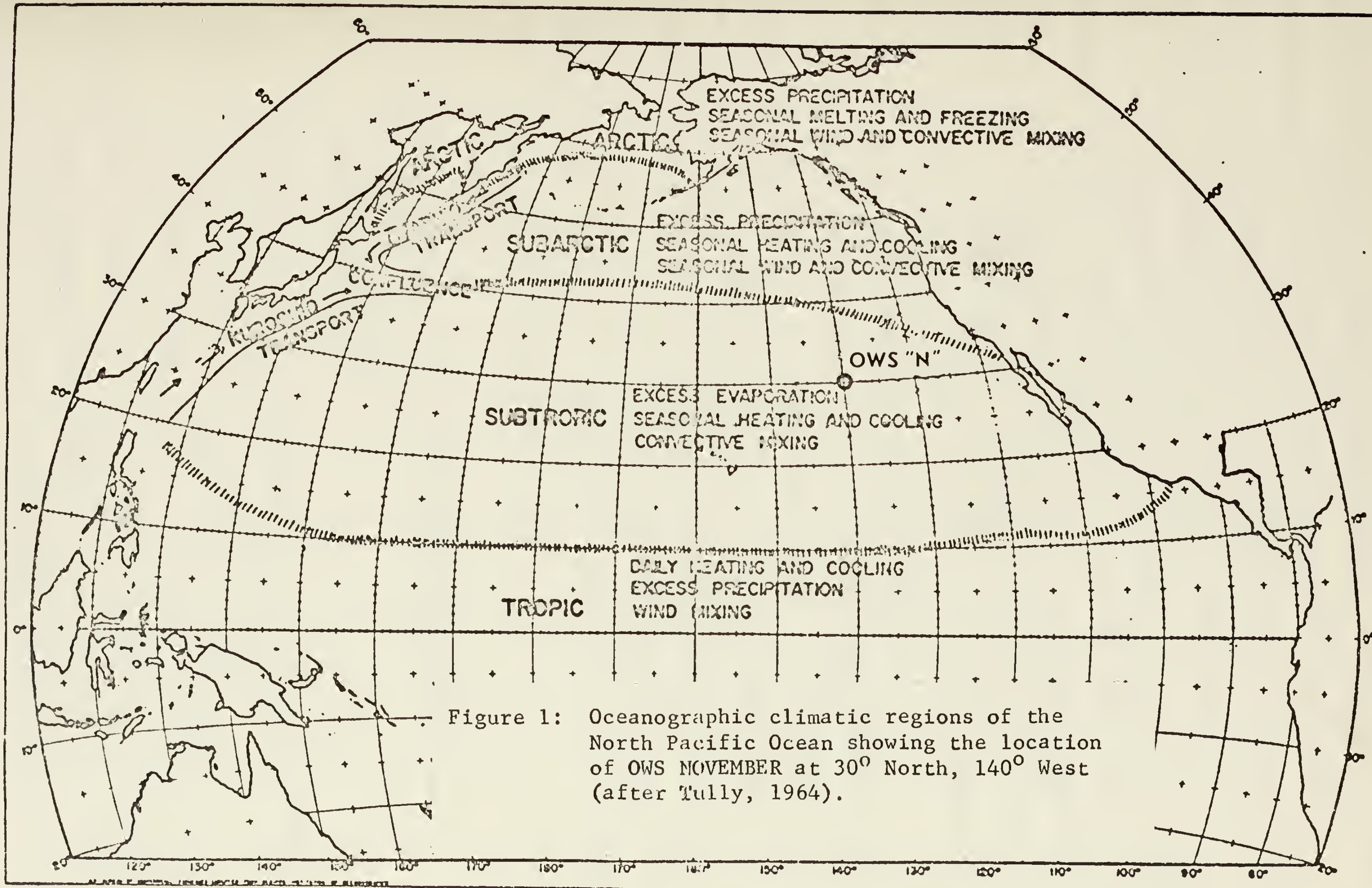

Figure 1: Oceanographic climatic regions of the North Pacific Ocean showing the location of OWS NOVEMBER at 30^{0} North, 140^{0} West (after Tully, 1964).

nature of the physical processes operating at the sea surface and have demonstrated how these processes affected the physical and dynamical properties of the surface water. Hansen [1973] studied the variations in temperature of the upper layers of the ocean. Correlations between temperatures at the surface and at selected depths as affected by the heat input were examined. Rabe [in press] in a follow-on study, analyzed the effects of various climatological parameters on sea surface temperature. Specifically, he determined those atmospheric mechanisms responsible for causing the observed fluctuations in the mean sea surface temperature and the response time associated with each mechanism.

In an attempt to further understand the mechanisms that alter the vertical distribution of sea surface temperature at OWS NOVEMBER, an examination of the importance and role of thermal advection and heat exchange is conducted. The procedure followed is based on a physical cause-effect principle using parameters that are easily calculated from routine meteorological and oceanographic observations. Each different influencing factor is evaluated separately.

A. REVIEW OF CLIMATOLOGY AND HYDROGRAPHY AT OWS NOVEMBER

1. Regional Oceanography

OWS NOVEMBER is located at 30°N latitude and 140°W longitude and lies in the northeast corner of the subtropic region.

Giovando and Robinson [1965, p. 2] define a region as "...an oceanic expanse featured by the characteristic and unique distribution of one or more oceanographic properties in the horizontal and/or the vertical direction." The North Pacific Ocean (NPO) has been divided into

regions according to the oceanographic properties of salinity and temperature. On the basis of the oceanographic properties four regions are formed--namely, tropic, subtropic, subarctic, and arctic (refer to Figure 1). The two regions of primary interest to this study, the subarctic and subtropic, have been identified by Dodimead, et al., [1963] according to the salinity structure.

The subtropic area is the largest of the four regions and contains the wind driven subtropic gyre. The subtropic gyre consists of the Kuroshio Current, the North Pacific Current, the California Current, and the North Equatorial Current. In the mid-ocean portion of the subtropic region the water flow is zonal; therefore, the surface water depends upon climatic conditions for its characteristics. In the eastern part of the subtropic region the flow is generally southward, and again the water adjusts to climatic conditions [Tully, 1963; Masuzawa, 1969]. Figures 2 and 3 [Department of Commerce, 1961] chart the winter and summer surface circulation patterns in the NPO.

In the subtropic region evaporation exceeds precipitation (E > P) throughout the year. Heating occurs from spring to autumn with September being the warmest month. Cooling dominates the remainder of the year with the lowest temperatures measured at the end of March. The seasonal thermocline separates the upper warm water from the deeper cooler water. An acceleration of the convective mixing process during the cooling season forms a distinctive mixed layer [Tully, 1963]. The temperature, salinity, and density structure of the subtropic region are schematically illustrated in Figure 4.

In the subtropic region there is a permanent thermocline located at approximately 100 to 150 m in depth. The permanent thermocline exists

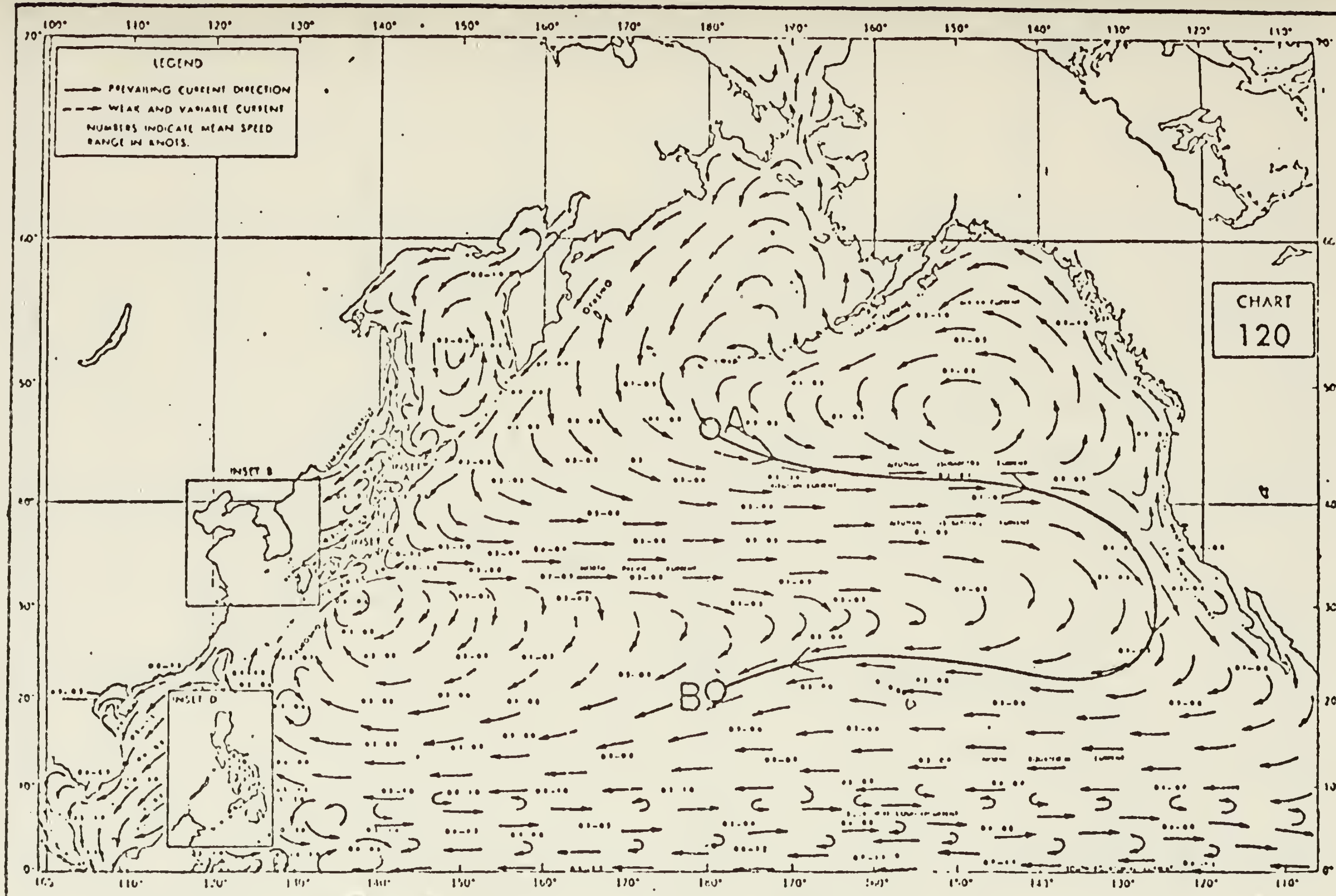

Figure 2 Winter surface circulation patterns for the North Pacific Ocean (Department of Commerce, 1961).

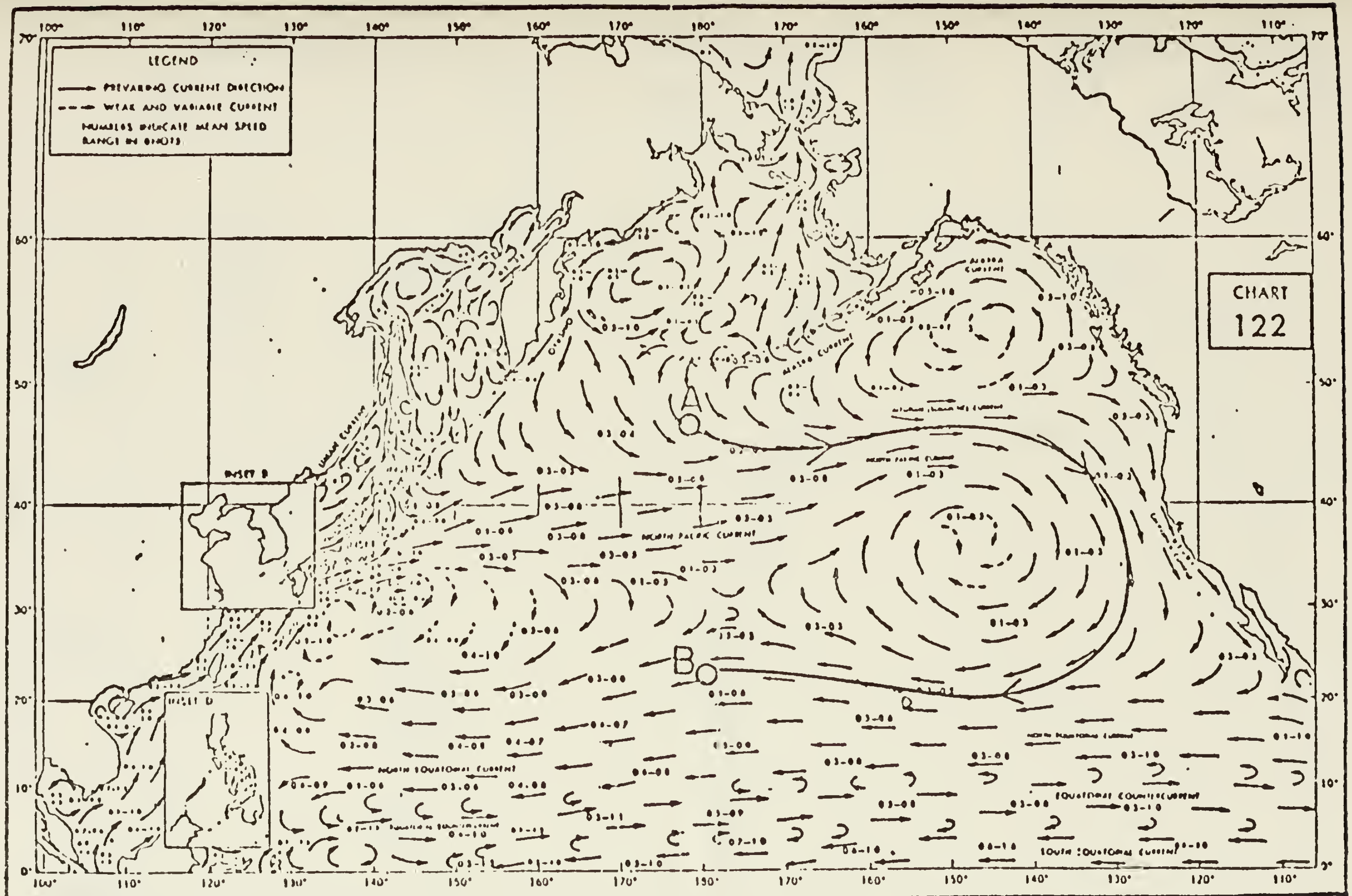

Figure 3. Summer surface circulation patterns for the North Pacific Ocean (Department of Commerce, 1961).

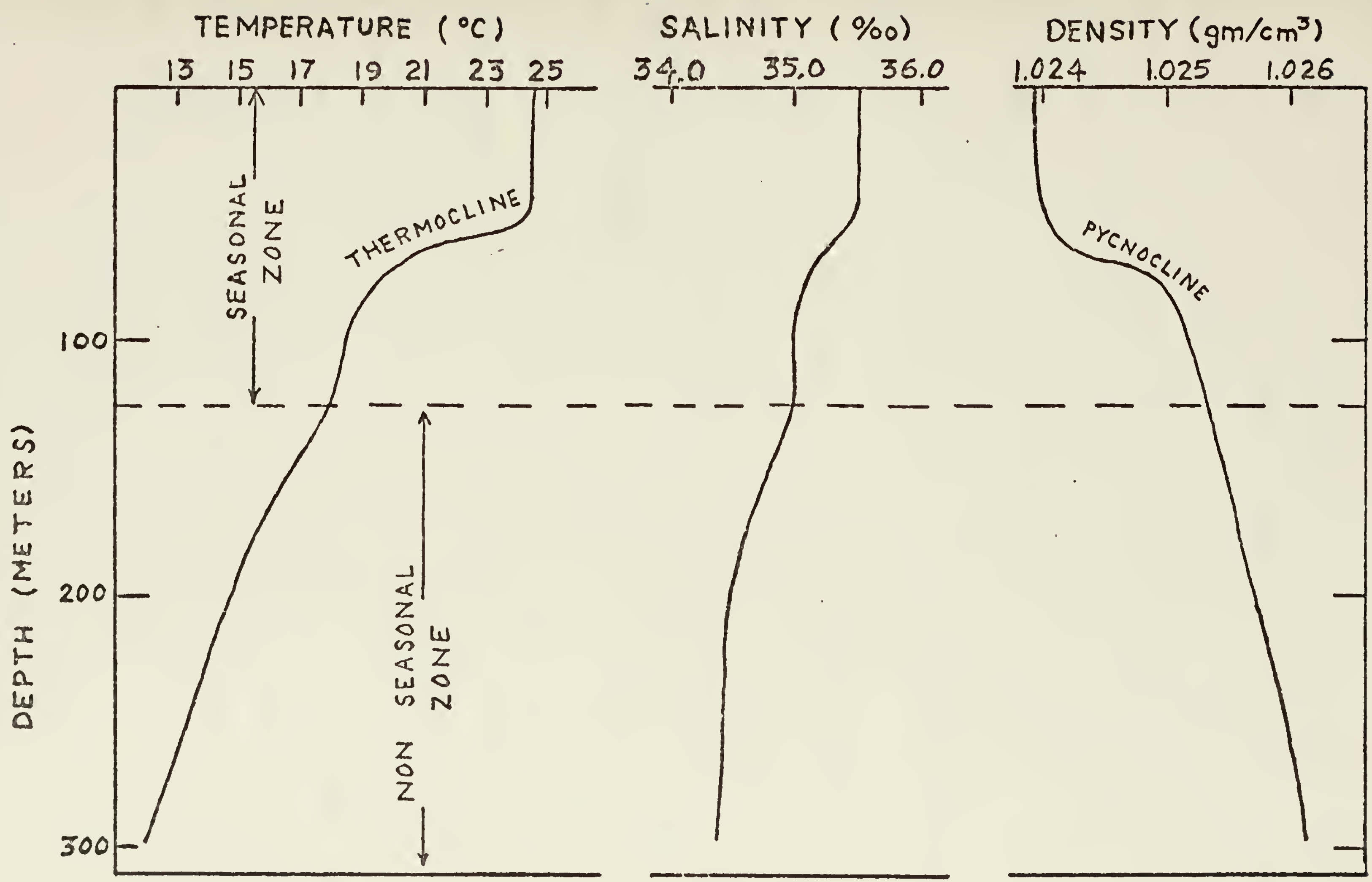

Figure 4: Typical temperature, salinity, and density structures in the Subtropic Pacific Ocean (after Tully, 1963).

because the seasonal zone never cools to the temperature of the non-seasonal zone [Tully, 1963].

North of the subtropic region is the subarctic region with characteristic structures as shown in Figure 5. In the subarctic region precipitation exceeds evaporation (P > E) creating a distinctive vertical salinity structure. In the summer a shallow isothermal layer is created by the excess precipitation preventing convective mixing. Mixing is primarily controlled by the wind at this time. In the winter the temperature drops sufficiently to override the excess precipitation producing convective mixing [Tully, 1961 and 1963; Dodimead and Pickard, 1967].

Separating the subtropic region from the subarctic region is a complicated boundary called the transition zone. The transition zone extends from Japan to North America and occupies a latitude belt between 32°N and 42°N latitude in the western and central part of the NPO. Approaching the North American continent the transition zone turns southeastward terminating around Baja California. The transition layer is marked by sharp horizontal salinity gradients and by breaks in the thin high stability layer encountered between 60 and 80 meters [Roden, 1971]. In the central Pacific the typical subarctic water mass, with its relatively cold and low salinity surface layer and its well-defined halocline, disappears within less than 100 km south of 42°N latitude. Proceeding southward the temperature and salinity gradually increase. Within 100 km north of 32°N latitude there is a sudden change toward warm, high saline water of subtropic origin [Roden, 1970].

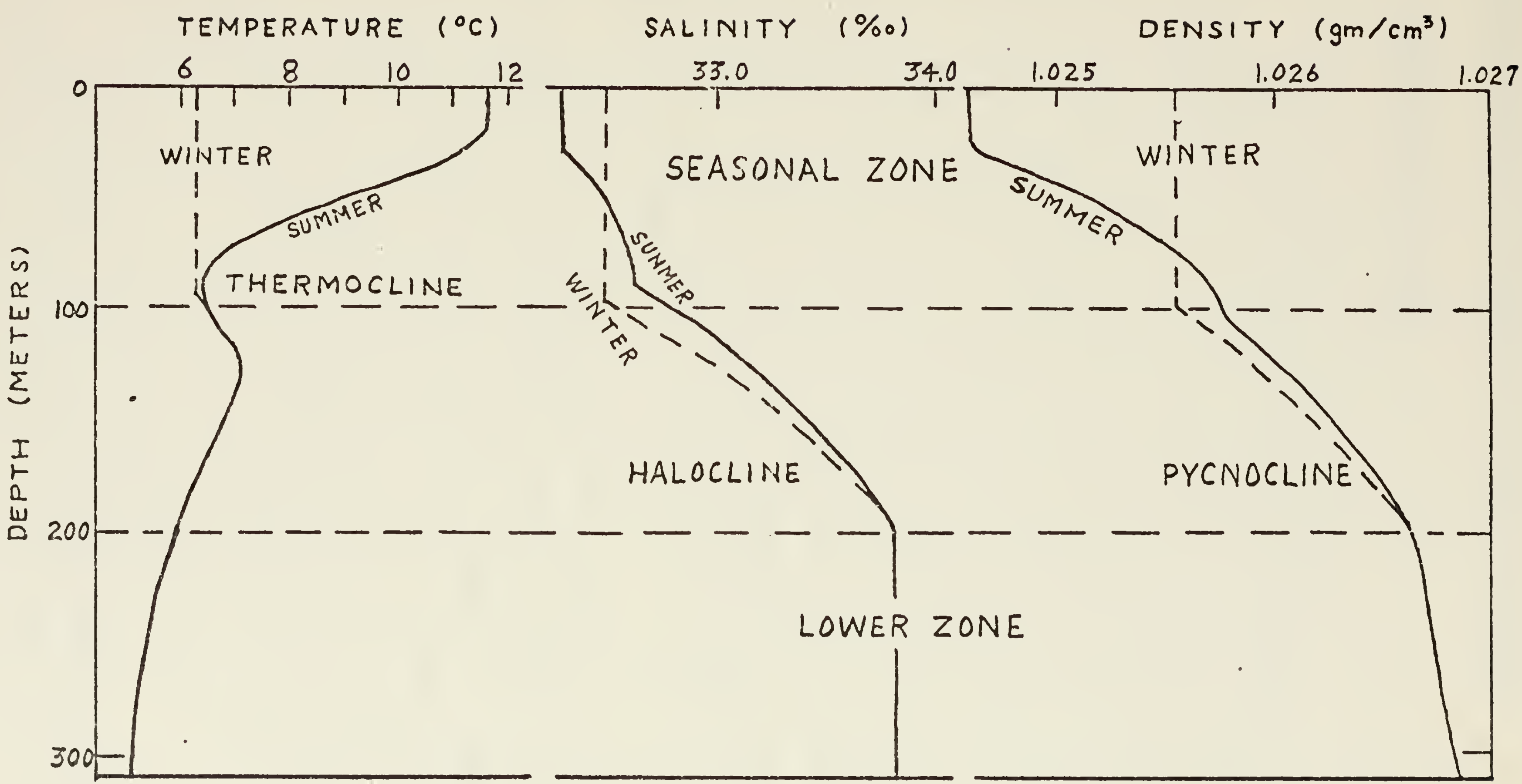

Figure 5: Typical temperature, salinity, and density structure in the Subarctic Pacific Ocean (after Tully, 1963).

B. PHYSICAL PROCESSES AFFECTING SEA SURFACE TEMPERATURE

1. Temperature Structure

a. Annual Variation of Surface Temperature

The SST and thermal structure are determined and modified by the sun and by forces and factors originating in the atmosphere. These forces and factors cause the sea temperature to undergo seasonal changes. According to Sverdrup, et al., [1942] the primary reasons for the annual variations of surface temperature in any region are the radiation income, the character of the ocean currents, and the prevailing wind.

In the subtropic region there is a seasonal cycle of heating and cooling which is maintained by heat exchange and mechanical wind mixing [Beland, 1971]. During the heating period the seasonal thermocline varies between 40 and 60 m and sinks to approximately 150 m during the cooling season. Figure 6 represents the seasonal changes in the thermal structure at OWS NOVEMBER.

Figure 7 illustrates the annual variation in the observed sea surface temperature at OWS NOVEMBER. Generally, heating occurs from April to mid-September with an increase in temperature of approximately 5°C for this period. The remainder of the year is dominated by cooling with the most rapid cooling occurring in October and November.

Sverdrup, et al., [1942] attribute the temperature range of the annual SST cycle primarily to the periodicity of incoming solar radiation.

b. Anomalous Sea Surface Temperatures

SST anomalies are often examined to obtain meaningful trends and abnormalities in surface temperature time series. While studying SST

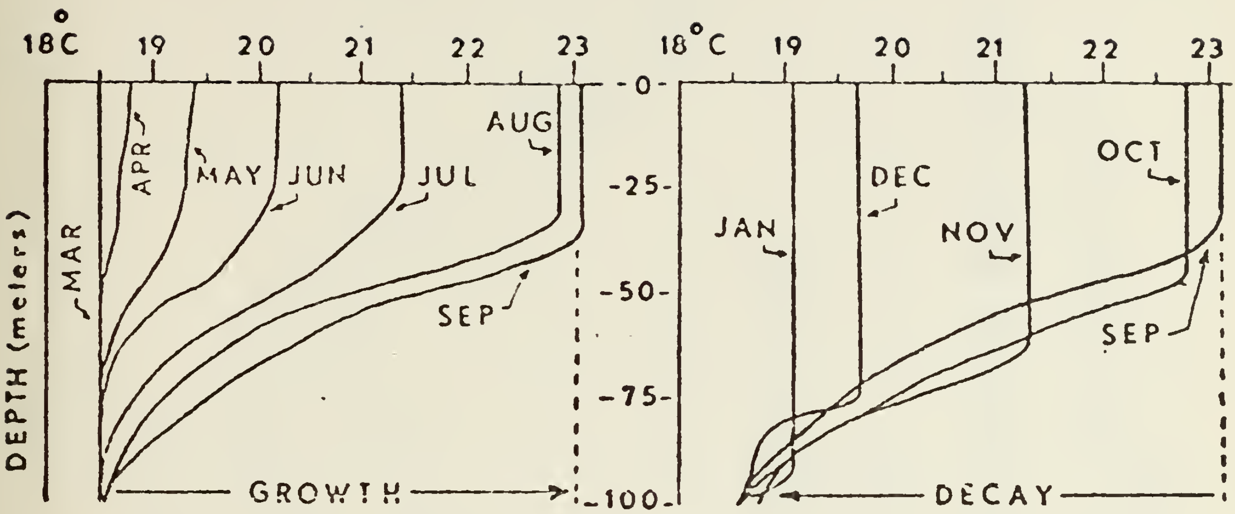

Figure 6: Schematic representation of the seasonal growth and decay of the thermocline at OWS NOVEMBER (after Beland, 1971).

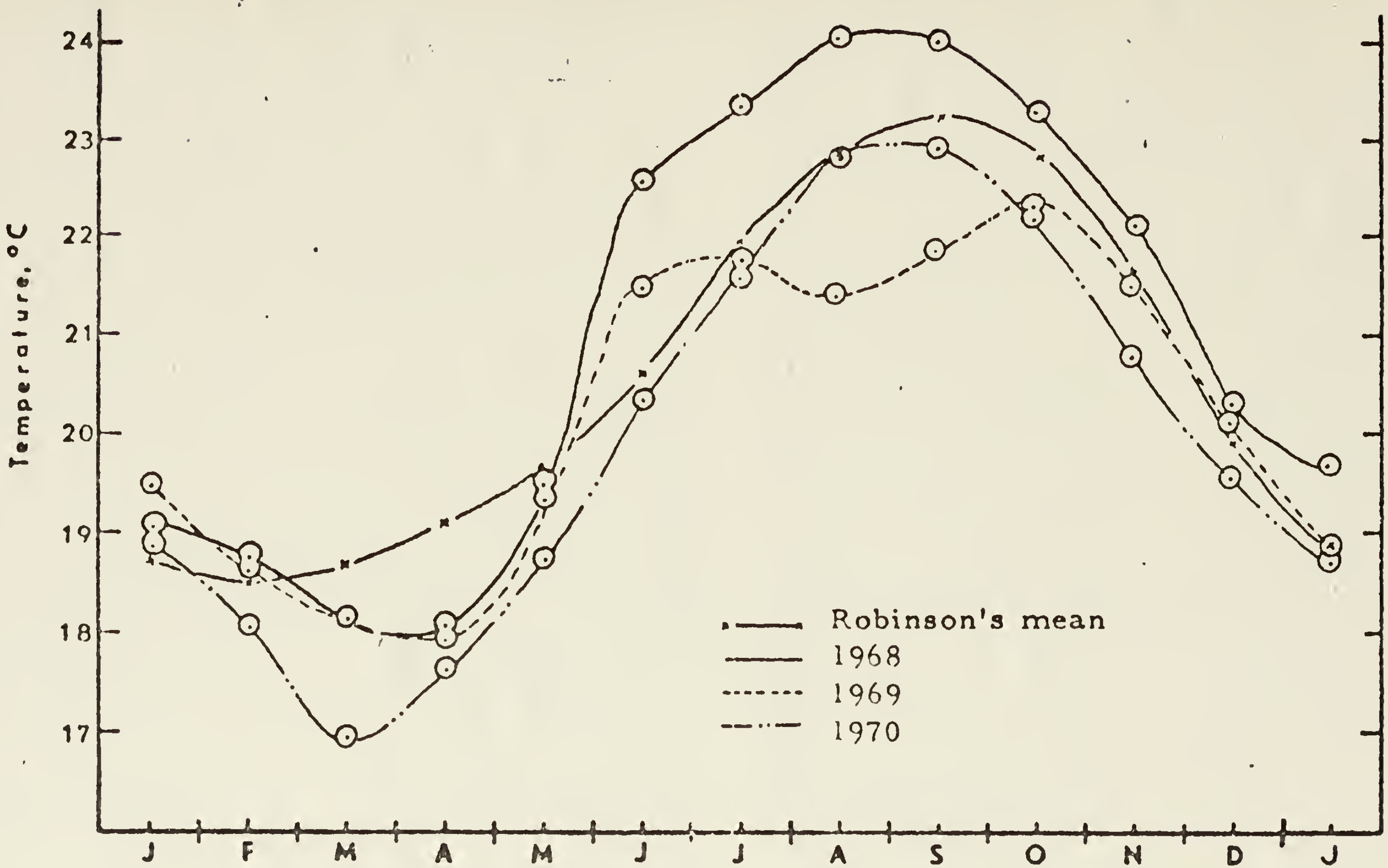

Figure 7. Monthly means of the observed surface temperatures, 1968 through 1970 and Robinson's (1971) long-term monthly means. (after Hansen, 1973).

anomalies and their possible effects on weather, Laevastu and Hubert [1970] found that SST anomalies change relatively rapidly in spring and autumn but can persist throughout the entire season during winter and summer. Taranto [1968], while investigating positive SST anomalies in the Northeast Pacific, concluded that these anomalies are formed and maintained by heat exchange, advection, and convergence (divergence) of surface currents.

SST anomalies develop very rapidly if anomalous climatic conditions prevail for any length of time. Namias [1970], in a brief report on temperal coherence between monthly mean temperature patterns for the sea surface in the NPO for the years 1947 - 1966, found a strong correlation of SST lag when using the months December through March. The lag was attributed to the deep mixed layer occurring at that time of the year.

In another study Namias [1971] observed an anomalous warming in the southern position of the NPO in May and June, 1968, and attributed it to bulk computations of heating. At OWS NOVEMBER one-third of the warming was accounted for by the heat exchange, exclusive of advection and mixing, with subsequent horizontal convergence of the surface water and associated downwelling. The remaining two-thirds of the heating was assumed to be accounted for by inward advection and downwelling of the insolation heated water from the large scale environment. Namias attributed the overall warming to the development and maintenance of a strong and deep Pacific anti-cyclone in June with its center located near OWS NOVEMBER. The nearness of the anti-cyclone center to OWS NOVEMBER suggested anomalous downwelling and possible Ekman transport of warm water from the south.

2. Net Heat Exchange

Heat exchange between the sea and atmosphere greatly affects the SST and thermal structure in the surface layer. The rate of absorption of solar energy, the most important source of energy, alters the thermal structure considerably but depends upon the optical properties of the water, radiation wavelengths, and salinity [Taranto, 1967].

At OWS NOBEMBER for the period 1951 - 1970 the average monthly mean values of the seasonal variations of net heat exchange and its processes are depicted in Figure 8. This chart clearly shows that the heat balance is dominated by the gain due to incoming shortwave radiation from the sun and sky and evaporation fluxes [Dorman, 1974].

A heat gain by the ocean during mid-April to mid-October in the decade, 1951 - 1960, is illustrated in Figure 8. In the following decade the heat gain occupied the same time interval but began in March. A maximum heat gain of 150 cal cm^{-2} day^{-1} in May during the first decade and 160 cal cm^{-2} day^{-1} in August of the second decade were computed.

Similarly, Wyrtki [1965] noted that the total heat exchange in the NPO is mainly determined by the incoming radiation and evaporation fluxes since back radiation is relatively constant and the sensible heat exchange is small.

3. Advection

Advection due to wind-driven currents in a given locality can substantially affect the variation of the SST patterns. In the formation of the SST patterns the direction of the advection is very important. Warm advection usually implies flow from the south and cold advection from the north. Advection plays an important role in some areas but is

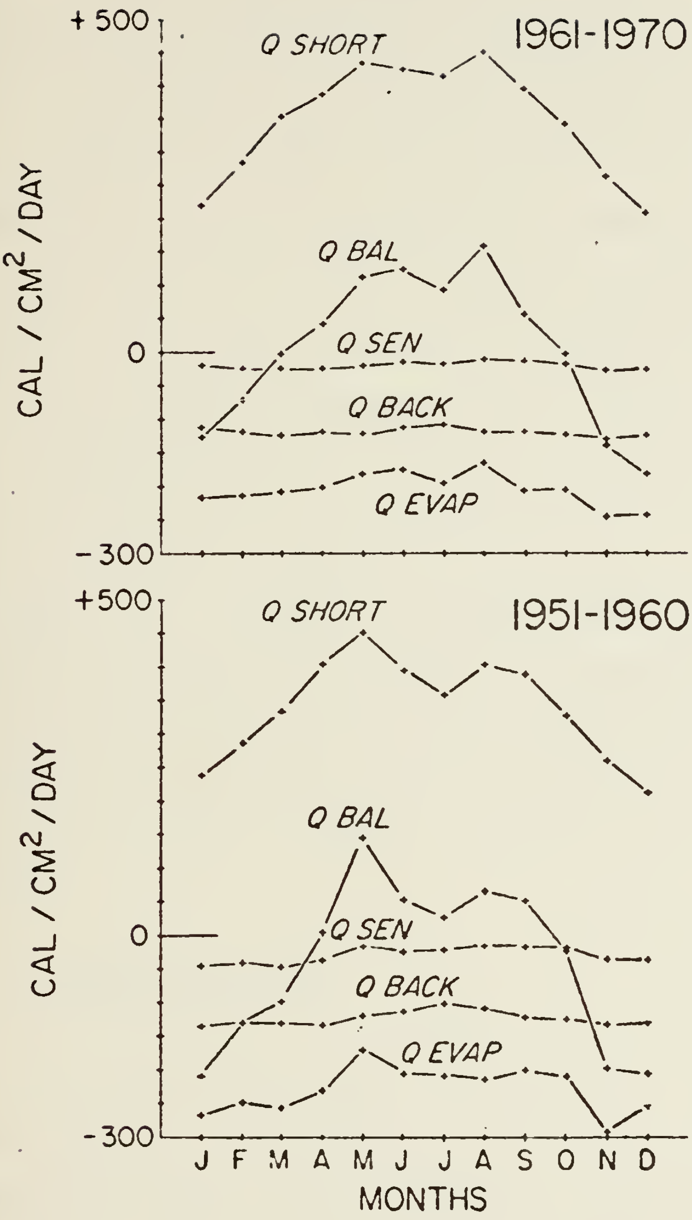

Figure 8: Heat balance for the two decades, 1951 - 1960, 1961 - 1970 (after Dorman, 1974).

completely dominated by heat exchange effects in other areas. Namias [1959] and Eber [1961] essentially reached this conclusion. Tabata [1961], during his study of heat budget consideration at OWS PAPA, found that the principal factor influencing the temperature in the upper zone of the ocean is the heat transfer at the air-sea boundary rather than advection.

SST reacts rapidly to the atmospheric forces; however, Taranto [1968] found a lag in the response of anomalous sea temperature to warm advection by at least a month. Evidence showed that the anomalous sea temperature continued to increase in magnitude even after the anomalous advection decreased or indicated a more northerly direction.

Bathen [1971] found that heat advection was twice as important as the net surface heat exchange in establishing the local thermal structure in the NPO. The processes he studied for the maintenance of the thermal structure were surface heat exchange, horizontal mixing, and horizontal advection with average annual values of 29%, 8%, and 63%, respectively, contributing to the local monthly change in the total heat storage in the NPO.

4. Mixed Layer Depth

The mixed layer depth is an important characteristic of the thermal structure. Clark [1972] found that it appears mixed layer depth anomalies have less effect on anomalous temperature changes during fall and winter. The greatest effect of the mixed layer depth fluctuation on the SST variation occurs during spring and summer with the largest effects occurring when the new seasonal thermocline is developing.

5. Surface Circulation

If the average distribution of temperature in the surface layer over a region is to be maintained, heat must be transferred from warmer regions to colder regions [Wyrtki, 1965]. Circulation and horizontal mixing maintain the average distribution of temperature in the surface layer.

Wyrtki reports that the average isotherms in the NPO are essentially zonal, and because they are zonal, meridional temperature gradients will cause a transfer of heat from the subtropic region towards the subarctic region. The transfer of heat is assumed to take place primarily in the mixed layer because of two factors--within the thermocline the horizontal eddy diffusivity is smaller and directly below the thermocline the horizontal temperature gradients are much weaker.

II. THEORY

A. GENERAL CONSIDERATIONS

The exchange of heat between the atmosphere and the ocean results from processes occurring at the sea surface. The heat budget equation describing this process for the whole ocean is

$$Q(N) = Q(S) - Q(B) - Q(E) - Q(C) \quad (1)$$

where Q(N) is the net heat exchange across the air-sea interface. When the sea water gains heat, Q(N) is positive and is negative when the sea water loses heat. The short and long wave radiation influxes are Q(S) and Q(B), respectively. The evaporation and sensible turbulent heat fluxes are Q(E) and Q(C), respectively.

According to Sverdrup, et al. [1942], when a specific region is considered, the local net heat exchange depends upon two factors--the heat brought into or out of the region by ocean currents or mixing processes and the amount of heat used for changing the temperature of the water over a certain peiod of time. The heat budget equation then becomes

$$Q(N) = Q(V) + Q(\theta) \quad (2)$$

where Q(V) is the advection term and $Q(\theta) = Q(S) - Q(B) - Q(E) - Q(C)$ and is the change in the temperature of the water due to surface exchange processes.

B. DERIVATION OF THE SIMPLIFIED TEMPERATURE CHANGE EQUATION

A procedure for monitoring the oceanographic conditions in ocean regions by means of time-sequence temperatures was described by Seckel

[1962]. He based this procedure on a simplified temperature budget equation which related observed monthly temperature changes to net heat exchange and horizontal advection. Following Seckel, the simplified heat budget equation is derived below.

At any locality in the ocean, net heat exchange across the sea surface must be balanced by the change in heat content of the water column, heat diffused through the sides of the column, and the heat carried in or out of the column by means of currents. With the assumptions that heat exchange across the sea surface is evenly distributed throughout the mixed layer and that vertical and lateral diffusion are negligible compared to horizontal advection and heat exchange across the sea surface, the simplified heat budget is expressed

$$\frac{\partial(\rho c_p \theta z)}{\partial t} = H - \nabla \cdot (\rho c_p \theta z\bar{V}) \tag{3}$$

where ρ is the density of the water, c_p is the specific heat of water, θ is the surface temperature assumed constant throughout the mixed layer, z is the depth of the mixed layer, and $\bar{V}$ is the horizontal velocity. $H \equiv Q(N)$ is the net heat exchange across the sea surface and ∇ is the two-dimensional operator.

The volume budget equation of the water column is

$$\frac{\partial z}{\partial t} = - \nabla \cdot (z\bar{V}) \tag{4}$$

An expansion of equations (3) and (4) results in

$$z\frac{\partial \theta}{\partial t} + \theta\frac{\partial z}{\partial t} = \frac{1}{\rho c_p}Q(N) - \theta z \nabla \cdot \bar{V} - \theta \bar{V} \cdot \nabla z - z\bar{V} \cdot \nabla \theta \tag{5}$$

$$\frac{\partial z}{\partial t} = -z \nabla \cdot \bar{V} - \bar{V} \cdot \nabla z \tag{6}$$

The constants are ρ and c_p; a typical value for ρc_p at OWS NOVEMBER is .978 g-cal cm^{-3} $^oC^{-1}$.

Subtracting equation (6) from (5) after multiplying equation (6) by θ leaves

$$z \frac{\partial \theta}{\partial t} = \frac{1}{\rho c_p} Q(N) - z\overline{V} \cdot \nabla \theta \qquad (7)$$

Then dividing through by z the temperature change equation for a unit mass of water becomes

$$\frac{\partial \theta}{\partial t} = \frac{1}{\rho c_p} \frac{Q(N)}{z} - \overline{V} \cdot \nabla \theta \qquad (8)$$

The units for the terms in the simplified temperature change equation are ^{o}C per month.

The term, $\frac{\partial \theta}{\partial t}$, is the local time change of temperature or the observed rate of change of temperature and its magnitude is determined from the combined effects of net heat exchange across the sea surface and heat advection.

The temperature of the water resulting from net heat exchange across the sea surface is modified by the depth through which the heat exchange is distributed and by the density and specific heat of the water. The net heat exchange is a process affecting the temperature per unit mass per unit time, $\frac{1}{\rho c_p} \frac{Q(N)}{z}$.

The second term which affects the water temperature is thermal advection, $\overline{V} \cdot \nabla \theta$, composed of the horizontal temperature distribution and velocity. Thermal advection is expressed in temperature per unit mass per unit time and should not be mistaken for the heat transport.

Expanding the vector notation, $\overline{V} \cdot \nabla \theta$, the thermal advection can be written $|\overline{V}| \, |\nabla \theta| \cos \phi$ where

$|\overline{V}|$ = magnitude of the velocity.

$|\nabla \theta|$ = magnitude of the temperature gradient.

ϕ = angle between the current and gradient direction.

When ϕ is zero, i.e. the current is flowing parallel to the isotherms, the advection is zero. However, the heat transport is not zero. Therefore, like the heat exchange process, thermal advection is also a process affecting the temperature of the water. Furthermore, in budget considerations, thermal advection will never give information about the component of velocity parallel to the isotherms even though velocity is present in the expression [Seckel, 1962].

C. THE CHARACTERISTIC ADVECTION DIAGRAM

If the rate of change of temperature, the net heat exchange, and the local mixed layer depth are known, the effect of advection on SST can then be determined by manipulation of the simplified temperature change equation. Seckel [1962] calculated and constructed graphs of the three terms of the simplified temperature change equation versus time for three locations in the Hawaiian Islands region and noted that the shape of the curves changed with location. However, at each location the heat exchange and rate of change of temperature curves possessed shapes and times of maxima and minima typical for their location. Due to the unique shapes and times of maxima and minima at particular locations, Seckel inferred that the rate of change of temperature curve could be called a characteristic heating curve, and since the combination of these curves determines the rate of change of temperature due to advection, similarily, characteristic advection curves. Figure 9 represents the so-called characteristic advection diagrams for particular locations in the Hawaiian Islands region as described by Seckel.

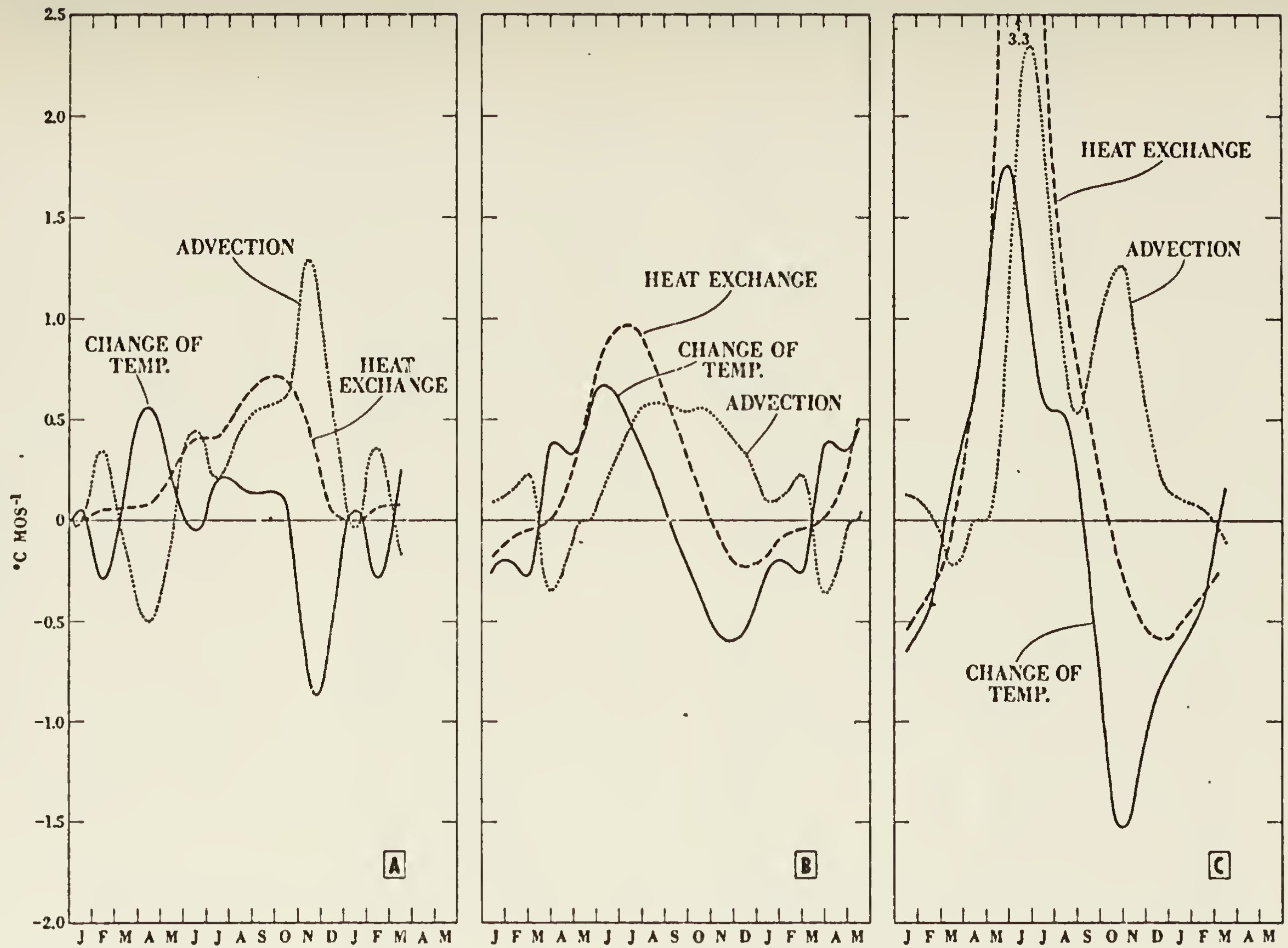

Figure 9: Characteristic advection diagrams for three locations in the Hawaiian Island region: A - 14° to 17°N, 156° to 159°W; B - 20° to 23°N, 156° to 159°W; and C - 26° to 29°N, 156° to 159°W (after Seckel, 1962).

III. ANALYSIS OF THE DATA

A. SOURCE OF THE DATA

The source of the data used in this study comes from the data file bank at the National Weather Record Center, Ashville, North Carolina, assembled from meteorological observations taken every three hours from United States Coast Guard weather ships at OWS NOVEMBER. The observations were taken during the years 1947 through 1970. Much of the data is incomplete before 1954 but has been interpolated and recorded manually. This study utilized the available data from 1954 through 1970. Rabe [in press] gives a complete resumé of the Ashville data file.

B. COMPUTATION OF HEAT EXCHANGE

The net heat exchange, Q(N), across the sea surface is comprised of several processes as shown by equation (1). The following empirical relationships for calculating the components of Q(N), as modified by Seckel [1970], are:

$$Q(S) = 0.95 Q_o K \tag{9}$$

$$\begin{aligned} Q(B) = {} & 1.14(10)^{-7} (273.16 + T_w)^4 (0.39 - 0.05 \sqrt{e_a}) \\ & (1 - 0.6C^2) + 4.58(10^{-7}) (273.16 + T_w)^3 \\ & (T_w - T_a) \end{aligned} \tag{10}$$

$$Q(E) = 3767 C_D (0.98 e_w - e_a) W \tag{11}$$

$$Q(C) = 4(T_w - T_a) W \tag{12}$$

The heat exchange components are expressed in cal cm^{-2} day^{-1}.

1. Insolation

Equation (9) represents the incoming shortwave radiation from the sun and sky. The incident solar radiation at a particular location is influenced by the altitude of the sun, the turbidity of the atmosphere, cloud cover, and reflectivity of the earth's surface [Duxbury, 1971]. The constant, 0.95, is the albedo factor which indicates that 5% of the incident radiation is lost due to reflection from the sea surface. The variable, K, is the cloud factor. Using a monthly mean total cloudiness for cumulus type clouds, the cloud factor formula [Seckel, 1970] is

$$K = 1 - 0.012C - 0.363C^2 \tag{13}$$

where C is the cloudiness in tenths of sky covered. The clear sky radiation (Q_o) is a function of latitude and day of the year. Expressed as a harmonic series Q_o is determined from Equation (14).

$$Q_o = A_o + A_1 \cos\phi + B_1 \sin\phi + A_2 \cos 2\phi + B_2 \sin 2\phi \tag{14}$$

where

$$\phi = \frac{2\pi}{365}(t - 21) \tag{15}$$

The A's and B's are coefficients in the harmonic series, and their values are taken from the Smithsonian Table [List, 1951]; t is the day of the year.

2. Effective Back Radiation

Equation (10) is the effective back radiation which is the difference between incoming and outgoing longwave radiation. Effective back radiation depends primarily on the temperature of the sea surface (T_w) and the water-vapor content of the atmosphere (e_a). The temperature of the sea surface is in degrees Celsius, and e_a, the vapor pressure, is

in millibars. The variable, C, is the cloudiness in tenths of sky covered, and T_a is the temperature of the air in degrees Celsius.

3. Evaporation

Equation (11) is the heat lost by the evaporation process. The saturation vapor pressure (e_w) is in millibars, and the wind speed (W) is in meters per second. A numerical value of 1.3×10^{-3} was used for the nondimensional drag coefficient (C_D) [G. Seckel, personal communication].

4. Sensible Heat

Equation (12) is the exchange of sensible heat across the sea surface and depends on the temperature difference between water and air and the wind speed. Seckel used a conduction factor of four.

C. COMPUTATION OF THE RATE OF CHANGE OF TEMPERATURE

The monthly averages for the SST time series was computed from bucket temperatures taken daily every three hours. From the average daily temperatures a monthly mean value for temperature was computed. Curves of these monthly mean temperature values were plotted, and temperatures for the first and last day of the month were tabulated over the seventeen year span. From this the monthly observed rate of change of temperature was determined.

D. CHANGE OF TEMPERATURE DUE TO ADVECTION

The magnitude of the advection was found by subtracting the monthly observed rate of change of temperature from the change of temperature

due to heat exchange. A positive advection implies transport of cold water into the local area, whereas a negative advection implies the transport of warm water into the region.

E. MIXED LAYER DEPTH (MLD)

The mean monthly MLD was obtained from mean monthly bathythermograph (BT) observations at OWS NOVEMBER digitized in 5m increments [Ballis, 1973]. The selection of the MLD is difficult and subjective, but from past experience the MLD can be adequately specified as the depth at which the temperature gradient exceeds $-0.2^{\circ}C/5m$.

The depth of the mixed layer varied from a long term mean of 144.7m for May to a long term mean of 39.4m for August. Over the seventeen year span each monthly mean MLD appeared to be relatively constant for all months except June where the depth of the layer varied from a minimum of 20 m to a maximum depth of 180m. The mixed layer structure for June consistently presented two negative thermal gradients greater than the $-0.2^{\circ}C/5m$ criteria for defining the bottom of the mixed layer. One thermal gradient occurred just below the sea surface and represented heat accumulated at the beginning of the warming season. The deeper thermal gradient occurred at approximately the same position as the previous month. This deeper thermal gradient was selected for the depth of the June mixed layer in all cases except when the shallower thermal gradient existed with some vertical extent and did not simply represent diurnal conditions. The mean monthly MLD computed over the seventeen years compared well with the mean monthly MLD charted by Bathen [1972] for the OWS NOVEMBER region.

IV. RESULTS

A. ANNUAL SST CYCLE

The calculated monthly means of observed surface temperature for the period 1954 through 1970 are plotted in Figure 10. As shown in this figure, OWS NOVEMBER undergoes a seasonal cycle of heating and cooling.

The season for net heating of the sea at OWS NOVEMBER is from mid-March to mid-September. The maximum value of 22.6°C occurs during September. Cooling dominates the period from mid-September to mid-March. March exhibits the minimum value of 18.2°C.

B. ANNUAL VARIATION IN THE MONTHLY MEANS OF THE TERMS IN THE SIMPLIFIED TEMPERATURE CHANGE EQUATION

Two conceptual approaches (Figures 11 and 12) depicting the annual variations in the monthly means of the rates of heat advection and heat exchange are the basis for the analysis of the collected data in this study. The graphs show the effects of each process on the observed rate of change of temperature. The principle of diagramming the data as displayed in Figure 11 was developed by Seckel [1962] and is referred to as the annual characteristic diagram for OWS NOVEMBER. Figure 12 is a numerical approach to the representation of the same data displayed in Figure 11 and lends itself to the forecasting of advection and heat exchange quite readily. The form of this presentation is based upon suggestions made by D. Leipper and G. Seckel. Three distinct trends of the local observed rate of change of temperature are clearly indicated in Figure 12.

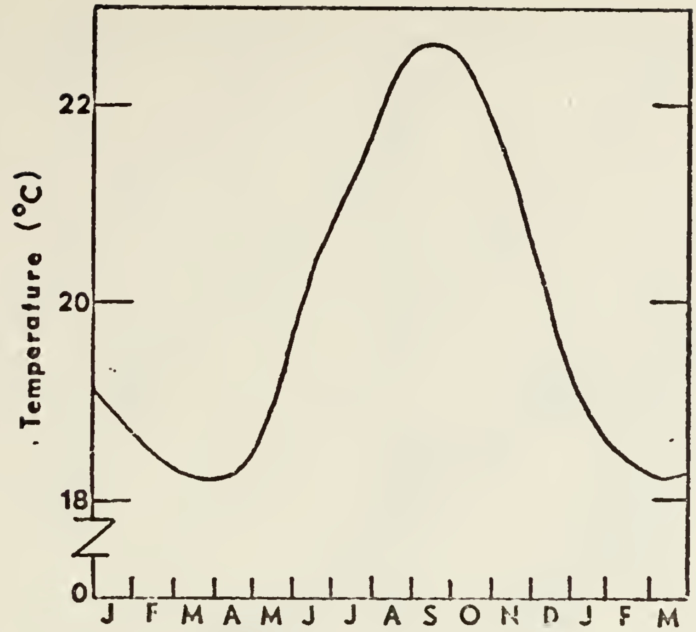

Figure 10: Monthly means of the observed surface temperature, 1954 through 1970.

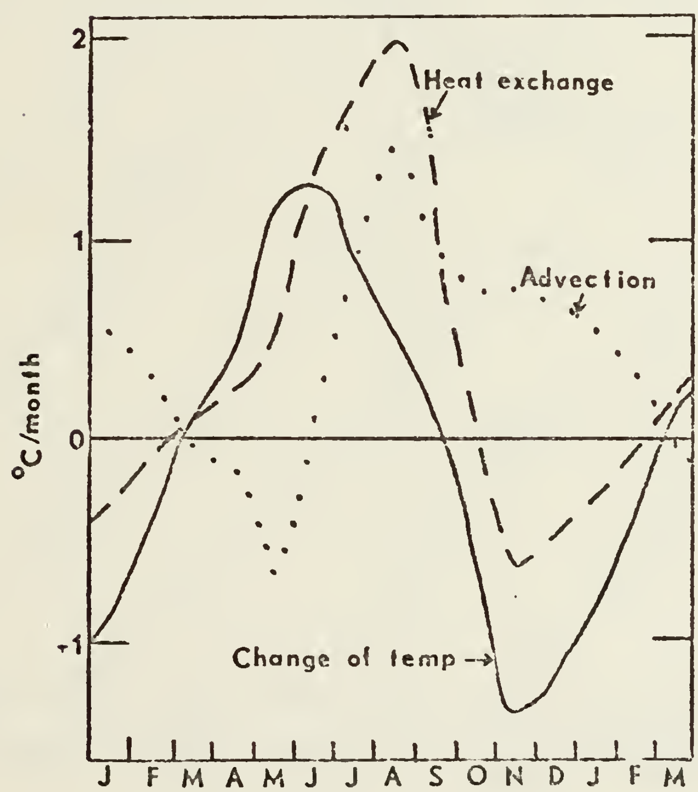

Figure 11: Average annual variation of mean monthly rate of observed temperature change and rate of temperature change due to heat exchange and thermal advection at OWS NOVEMBER.

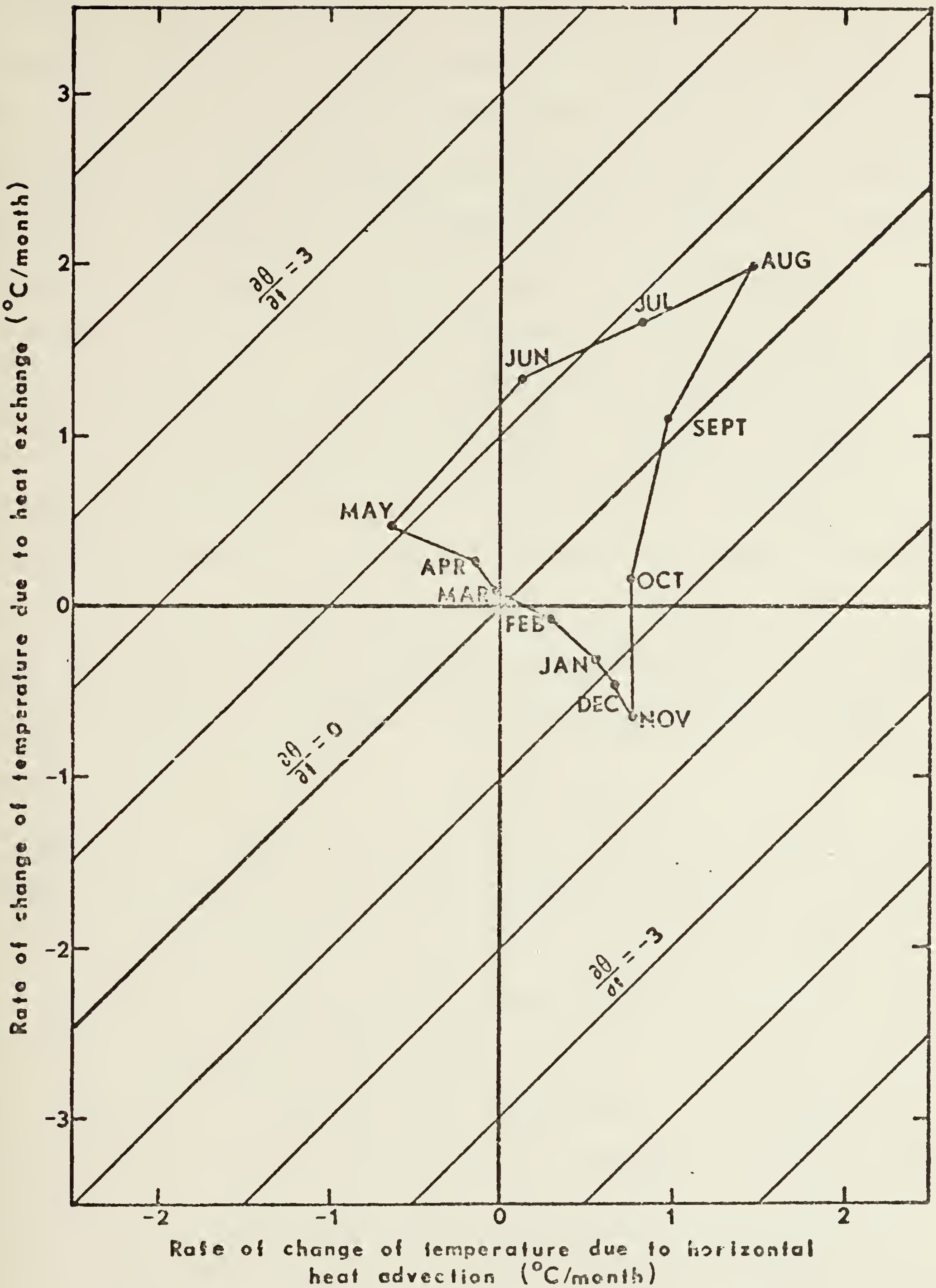

Figure 12: Annual variation of the monthly means at OWS NOVEMBER. Warm advection is to the left of the zero line of the abscissa while cold advection is to the right. Positive heat exchange occurs above the zero line of the ordinate and is heat gained by the ocean. Negative heat exchange or heat loss by the ocean occurs below the zero line. The 45° lines represent the observed rate of change of temperature.

The observed rate of change of temperature remains relatively constant in the first trend. From May to August the temperature of the water increases at the constant rate of approximately 1°C/month. This relatively constant observed rate of change of temperature interval corresponds to the steady increasing SST of the heating season. The rate of increase is moderated by the constantly increasing influx of cool water.

The observed rate of change of temperature for May was caused by an influx of heat from two sources--0.68°C/month rate increase due to advection and 0.47°C/month by heat exchange. From May to August the observed increase in SST was sustained mainly by an increasing heat exchange which reached a maximum of 1.98°C/month in August. During this time warm advection ceased and warm summer temperatures were held in check by increasingly larger advection rates of cooler water reaching a maximum in August of 1.45°C/month concurrent with the heat exchange maximum.

Figure 13, a combined modal analysis of sea surface temperature and salinity based on daily observations from 1968 through 1970, illustrates a steady increase in SST from May to August. During May and June the salinity content of the water is increasing--an indication of an influx of warm water. Then, from June to August advection of cold water contributes to a decline in the salinity content. Therefore, by correlating the observed rate of change of temperature, as affected by advection and heat exchange shown in Figure 12, and the surface salinity content of the ocean, as depicted in Figure 13, it can be inferred that heat exchange is the major contributing factor to the rise in SST for the first trend but its contribution is moderated by advection of cooler water.

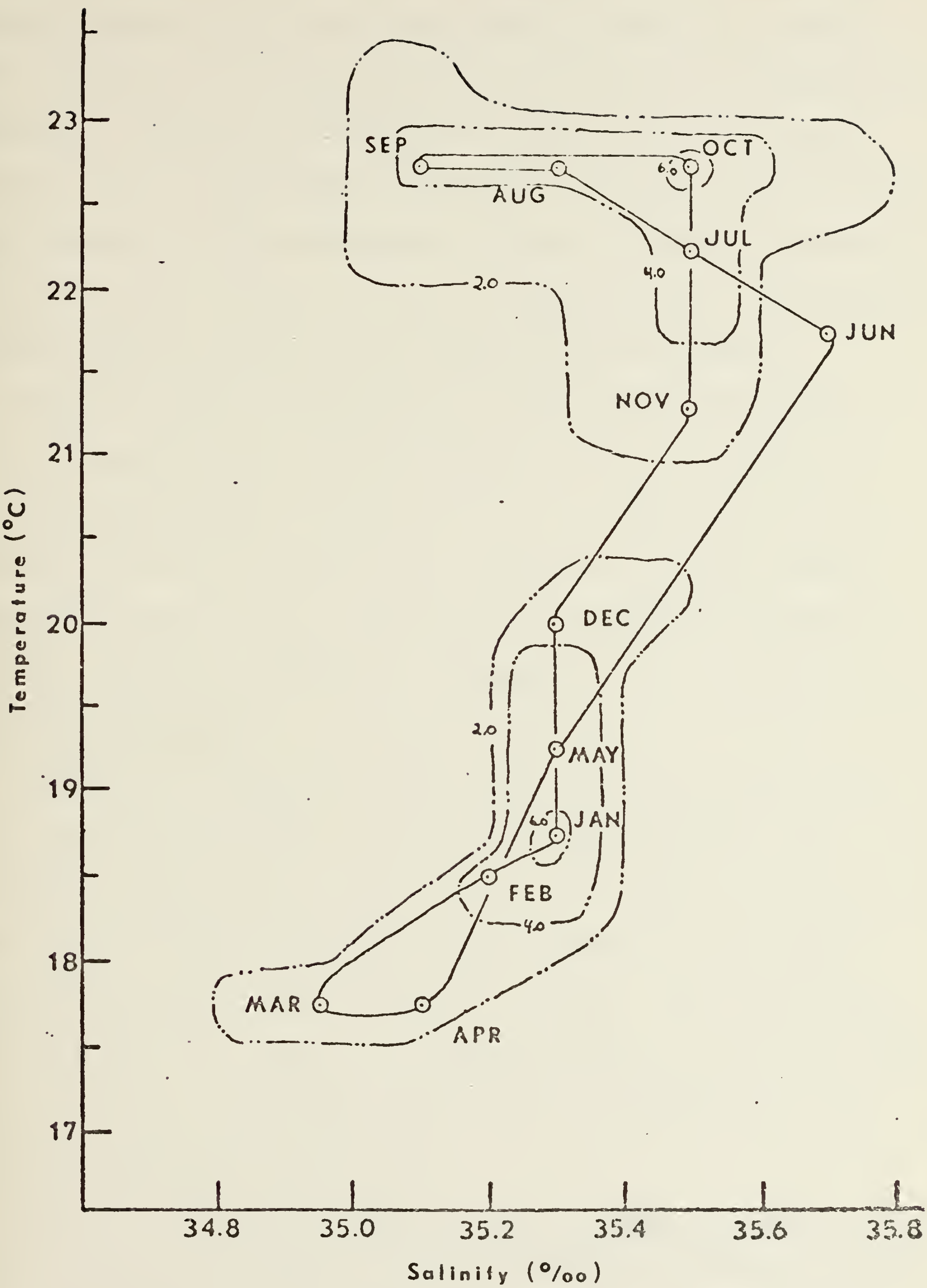

Figure 13: Monthly temperature and salinity modal points resulting from the bi-variate analysis of the data, 1968 through 1970 (after Hansen, 1973).

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From August to November the SST (Figure 10) initially experiences a gradual increase until the peak temperature is reached in September. Then the SST begins to decrease and the observed rate of cooling steadily increases. Advection of cold water is present, but at a relatively constant value of approximately 0.8°C/month. Figure 13 illustrates that from September to October the surface salinity increases in response to a decrease in the advection of cool, low salinity water. From October to November surface salinity and the advection rate are constant.

The major reason for the decline in the SST during this period is that, although the sea is receiving more heat than it is giving off (August through October), the rate at which it receives heat steadily decreases. The rate at which heat is supplied to the ocean from the atmosphere decreases from a maximum value of 1.98°C/month in August to a yearly minimum of -0.63°C/month in November; i.e., the ocean gives up heat to the atmosphere.

From August to September the SST continues to rise but at a slower rate until the maximum SST of 22.6°C is reached in September. The rate of change of temperature is essentially zero for September and afterwards continues to decline gradually reaching its maximum observed rate of change of temperature of -1.39°C/month in November. The -1.39°C/month decline in SST is the result of the seasonal maximum rate of loss of heat from the ocean of -0.63°C/month coupled with a -0.76°C/month rate of cooling by advection of cold water.

The third trend occupies the time period November through May. During this interval the SST (Figures 10 and 13) continues to gradually decline at a slower rate until the minimum SST of 18.2°C is reached in March. The rate of heat lost from the ocean and the rate of advection of cold water

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steadily diminish until March when they are near zero. They are nearly equal in magnitude for the months of December and January. By February both rates are approaching zero but with the advection of cold water continuing to decrease the SST by a rate of -0.3^{o}C/month.

The annual SST cycle exhibits its minimum value in March when the observed rate of change of temperature is zero. This indicates that the contributions to heating by advection and heat exchange are nearly zero. A gradual increase in SST and surface salinity then ensues in April and May corresponding to steadily increasing rates of warm advection (with its greater salinity) and heat exchange with the rate of warming due to advection exceeding heat exchange in May.

C. THE YEAR, 1955

A number of anomalously warm or cold years were selected for analysis. The characteristic advection diagrams and bar graphs of the three terms in the simplified temperature budget equation for these years are included in Appendix A.

The year, 1955, was specifically selected for analysis because it was predominantly a cold year. Figure 14, the SST anomaly bar graph, clearly illustrates the presence of abnormally low surface temperatures during most of the year. Although the SST measured in March, April, and November averages 1^{o}C above the norm, a below normal average of 0.8^{o}C was recorded for the remainder of the year.

Prior to the below normal SST phase (May through October), short periods (two months) of alternating above and below normal SST occurred. An abnormally low SST was recorded in January and was caused by an anomalous rate of cooling by advection, nearly twice the normally

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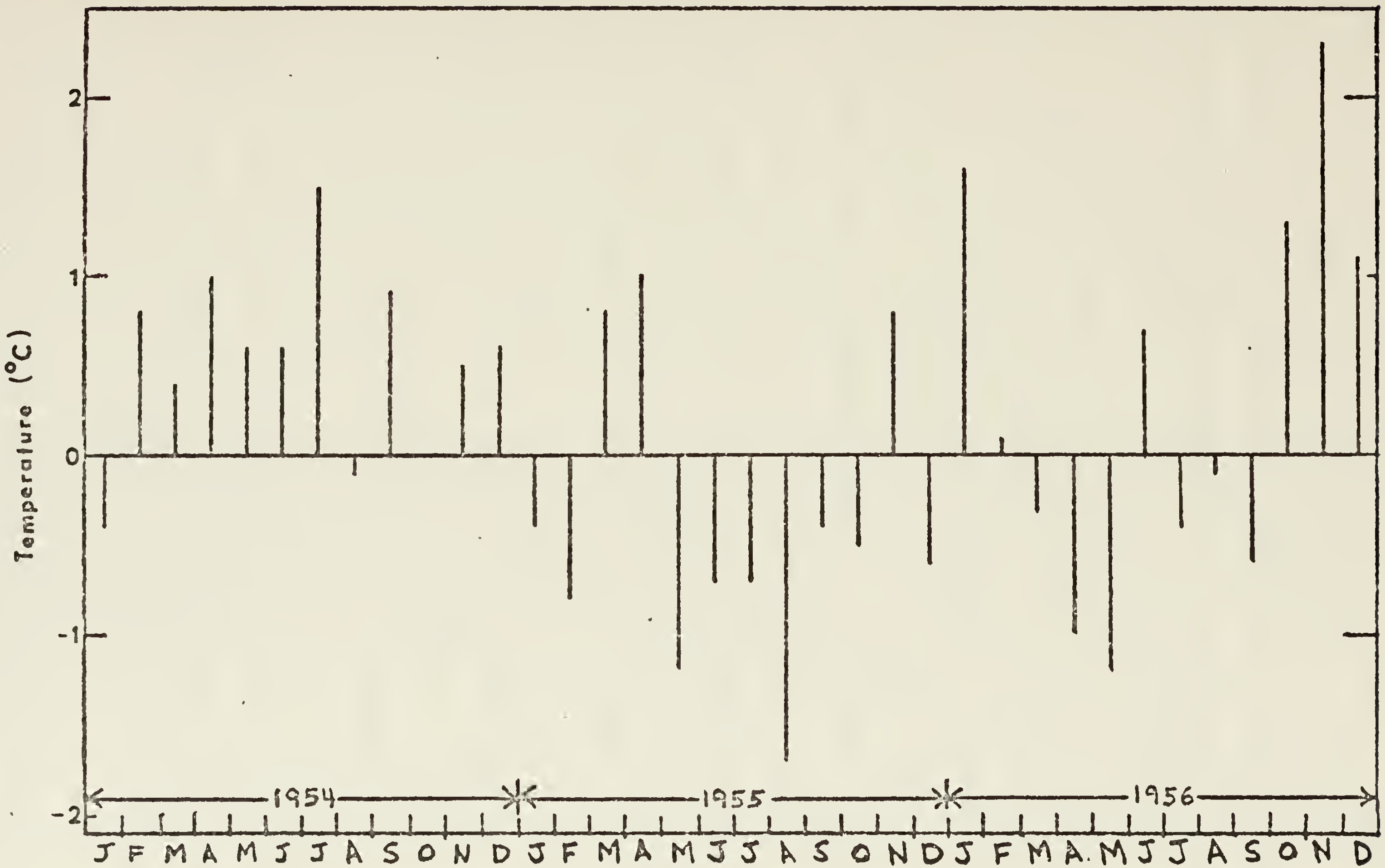

Figure 14: Monthly mean SST anomaly for 1955. Positive values indicate higher temperatures than normal; negative values indicate lower temperatures than normal.

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occurring rate, while the heat exchange process remained normal. The SST pattern continued to decline in February even though the contribution of normal heat exchange and above normal rate of warming by advection would indicate above normal SST. This indicates a lag of SST in response to the anomalous rate of cooling due to advection in January (Figure 15).

During the months, March through May, the observed rate of change of temperature is dominated by the advection process varying from a maximum rate of 1.20°C/month in March, a result of an influx of warm water, to a rate of 0.56°C/month in both April and May, the end product of advection of cooler water. In March the rate of warming due to advection was moderated by an above normal heat loss from the ocean, while in April the slightly below normal heat exchange aided in the increase in the rate of cooling. The heat exchange process was normal in May. Figure 14 indicates above normal warming in March and April, but as previously explained, the combined effects of the rates of advection and heat exchange indicate an anomalous warming in March and anomalous cooling in April. The lag in the SST for April is assumed to be in response to the above normal rate of warming due to advection which occurred the previous month.

In June the observed rate of change of temperature increased from that of May and was slightly greater than the long-term mean for June as a result of the abnormally large influx of warmer water creating a 1.10°C/month rate increase in conjunction with a below normal gain of heat by the ocean (0.35°C/month). But in June the SST still registered below normal temperatures even though the abnormally high influx of warm water dominated.

An above normal rate of heat gained by the ocean diminished by a slightly below normal rate of cooling by advection in October produced

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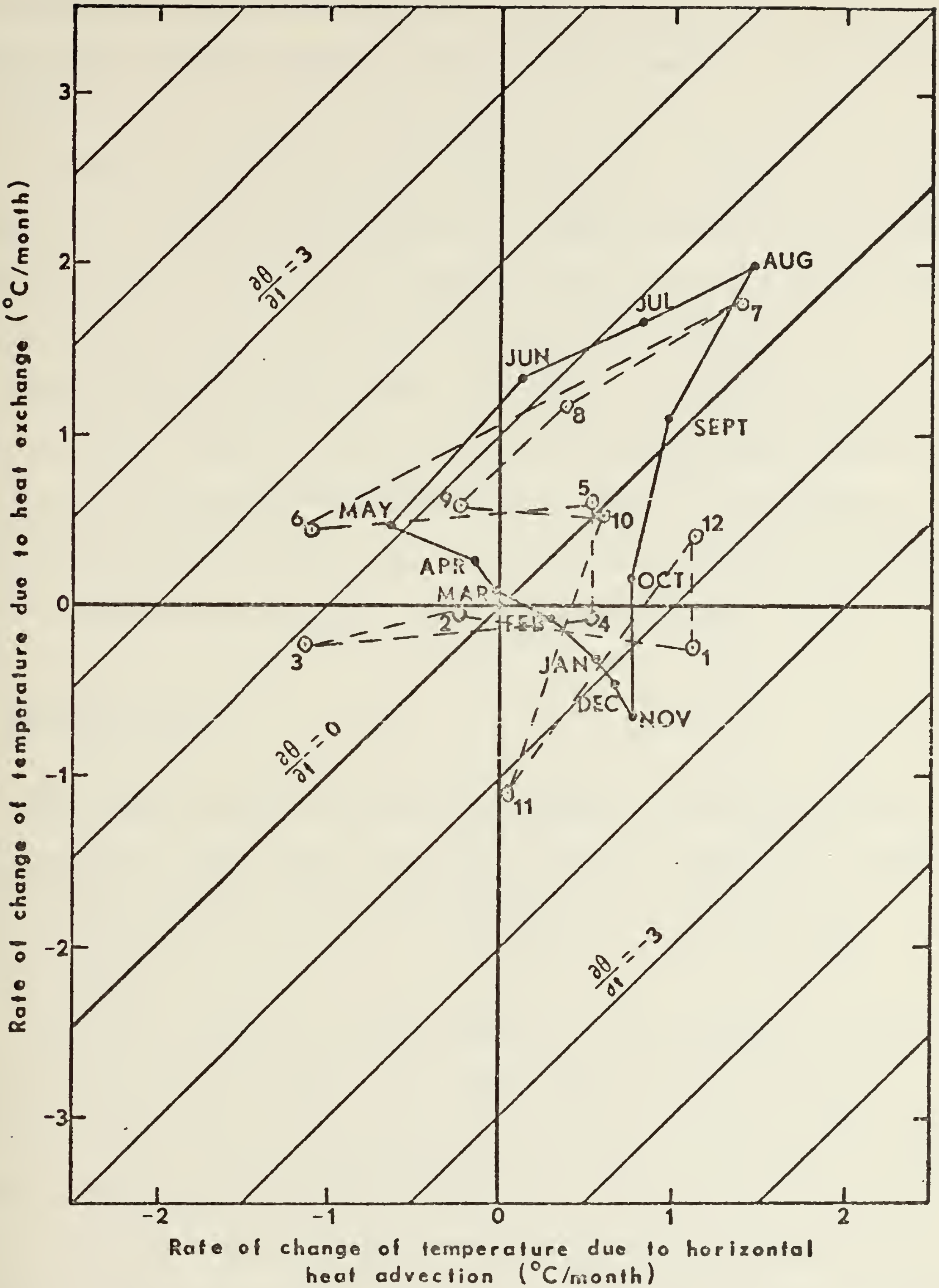

Figure 15: Observed variations of the monthly means for 1955 (broken line) at OWS NOVEMBER. (1 - Jan., 2 - Feb., etc.). The solid line represents the annual variation of the monthly means. Plus values indicate warming by heat exchange and cooling by advection.

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an above normal SST during November. This is the only case in point during 1955 when heat exchange proved to be the dominant process affecting the SST.

A complete reversal from the above normal SST in November to a below normal SST in December then took place. During November heat loss from the ocean was twice as great as normally experienced while the advection of cold water is near zero (normal value is 0.76°C/month).

Hanzawa [1958] indicated that in 1955 the Pacific High was more developed than usual and produced an above average anomalous transport of water in the southeastern North Pacific. Because of the intense Pacific High and associated winds, increased volumes of colder northern water were most likely brought into the southeastern NPO.

D. THE YEAR, 1957

Above normal monthly mean SSTs were recorded in 1957 with the one exception of a -0.4°C anomaly measured in February (Figure 16). Unusually high anomalous SST of 2.5°C and 2.4°C occurred in April and June, respectively.

In January an above normal SST anomaly is still present as a carry over from the previous month. The below average rate of cooling in January is the result of an anomalous loss of heat from the ocean combined with a normal rate of advection (Figure 17). Then in February an above normal rate of cooling by advection associated with a normal rate of heat exchange interact to produce a further diminishing of the rate of cooling. An inference of a lag of the SST in February in response to the large rate of cooling in January is not apparent since February also exhibited an abnormal rate of cooling. One statement that can be made concerning

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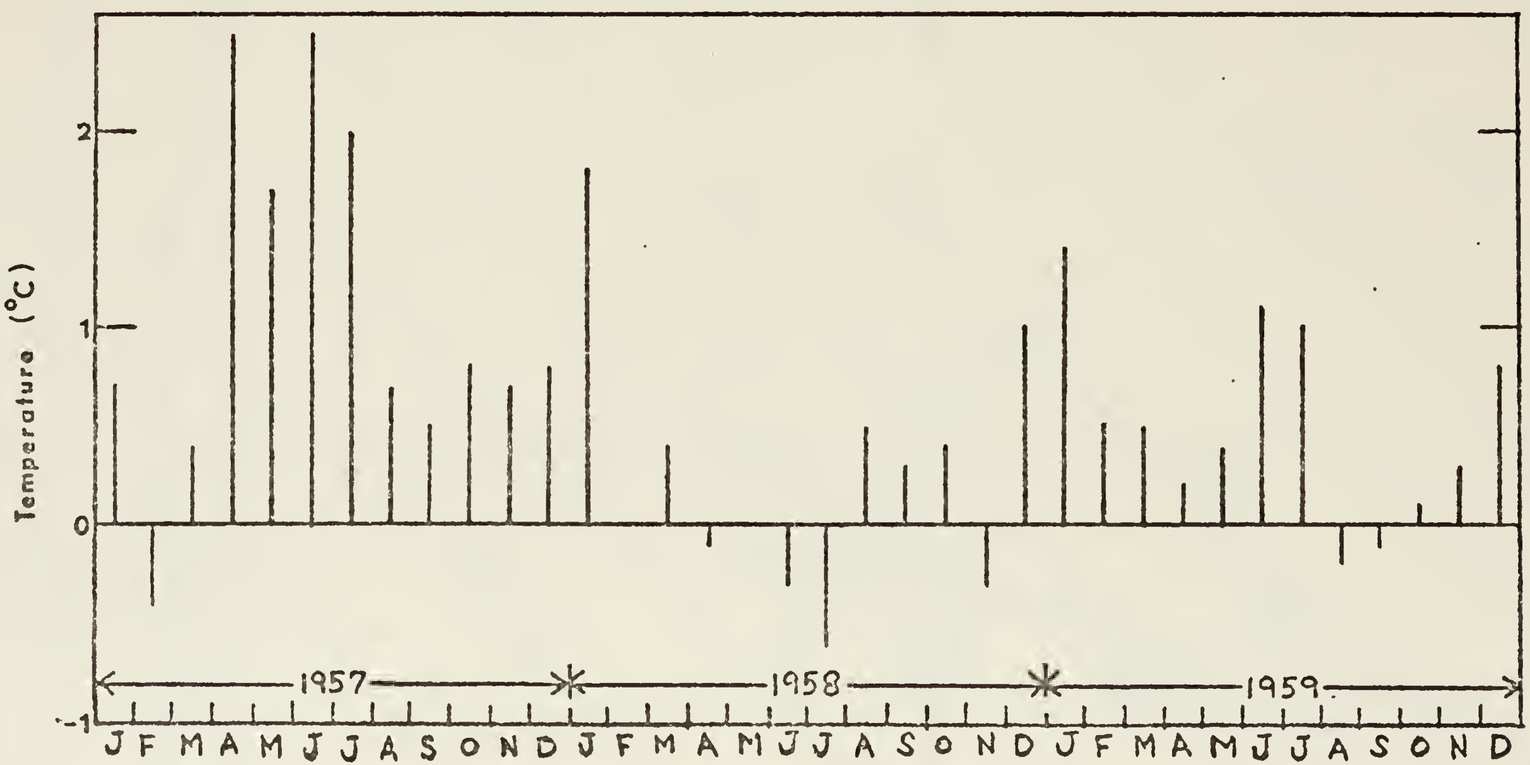

Figure 16: Monthly mean SST anomaly for 1957. Positive values indicate higher temperatures than normal; negative values indicate lower temperatures than normal.

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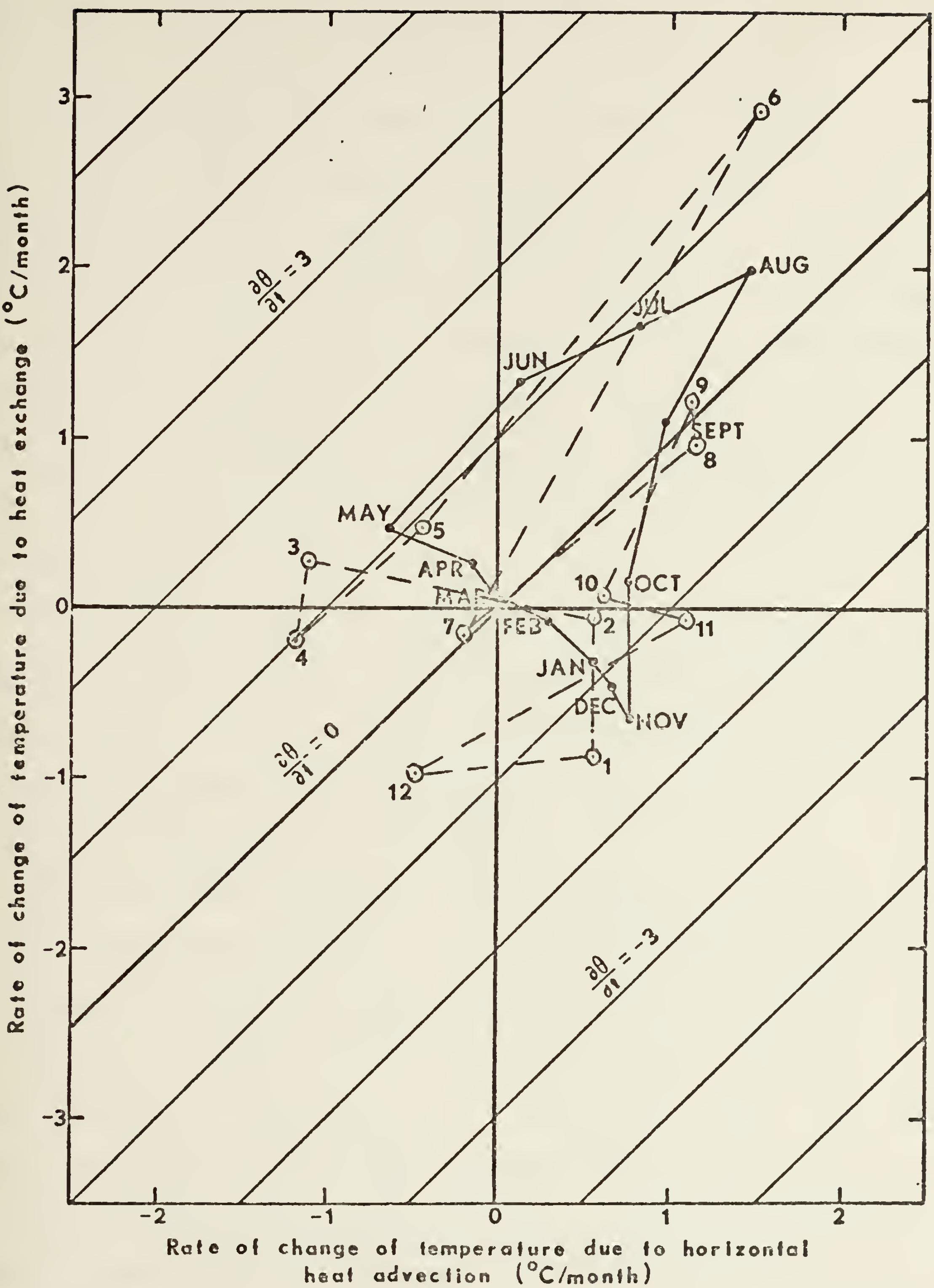

Figure 17: Observed variations of the monthly means for 1957 (broken line) at OWS NOVEMBER. (1 - Jan., 2 - Feb., etc.). The solid line represents the annual variation of the monthly means. Plus values indicate warming by heat exchange and cooling by advection.

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the change in SST is that a below normal SST would be the result of abnormal cooling conditions occurring in January and February.

Typically in March the observed rate of temperature change is near zero since the rates of temperature change due to advection and heat exchange are near zero. However, in March and April of 1957 the rate of warming of the water was unusually high (approximately 1 - 1.5^{o}C/month) due to a large influx of heat by advection. The effect of this abnormal warming is only partially observed in March with most of the effect appearing in April which was 2.5^{o}C warmer than usual. Heat rates are near normal in May but the warmer SST anomaly is still present as a carry over from the previous month.

In June SST are again much warmer than normal (2.4^{o}C higher) primarily because the rate of warming by heat exchange, already at a fairly high value in June, is twice that normally experienced. The maximum rate of warming usually observed in May occurred in June in response to the rapid rate of heating from the atmosphere.

From July through September the rate of change of temperature is near zero but SSTs remain abnormally high, although the SST anomaly steadily decreased, because of the excess heat provided during April through June.

During the remainder of the year SSTs were higher than normal, with heat exchange and advection processes at near normal levels. The higher than normal SSTs were most likely sustained by the residual heat acquired during the spring. In November and December the positive SST anomalies were maintained by markedly reduced rates of cooling by heat exchange in November and advection in December.

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E. THE YEAR, 1960

Above normal SSTs characterized the first half of 1960 with the maximum SST anomaly of 1.0°C occurring in May. Anomalous cooling prevailed throughout the remainder of the year. The minimum SST anomaly of -0.8°C was measured in September (Figure 18).

Trends of the observed rate of change of temperature are obvious in Figure 19 and are quite similar to the trends of the annual variations of the monthly means.

From January through April the sustained positive SST anomaly is maintained by a combination of reduced cooling rates by advection and increased rates of warming by heat exchange.

A relatively constant observed rate of increase of temperature of 0.8°C/month occurs from April through July as compared with a normal rate of 1.0°C/month. This moderate reduction in the heating rate lead to SSTs becoming cooler than normal during June and July.

The rate of warming due to heat exchange processes was substantially lower than normal in August and September; hence SSTs were cooler than the average for these months and remained so for the rest of the year even though near normal conditions prevailed.

F. THE YEAR, 1962

The year, 1962, was predominantly a warm year as is illustrated by Figure 18. In January, March, and June below normal SSTs were registered. A maximum SST anomaly of 0.9°C occurred in May, and the minimum SST anomaly of 0.7°C was recorded in March.

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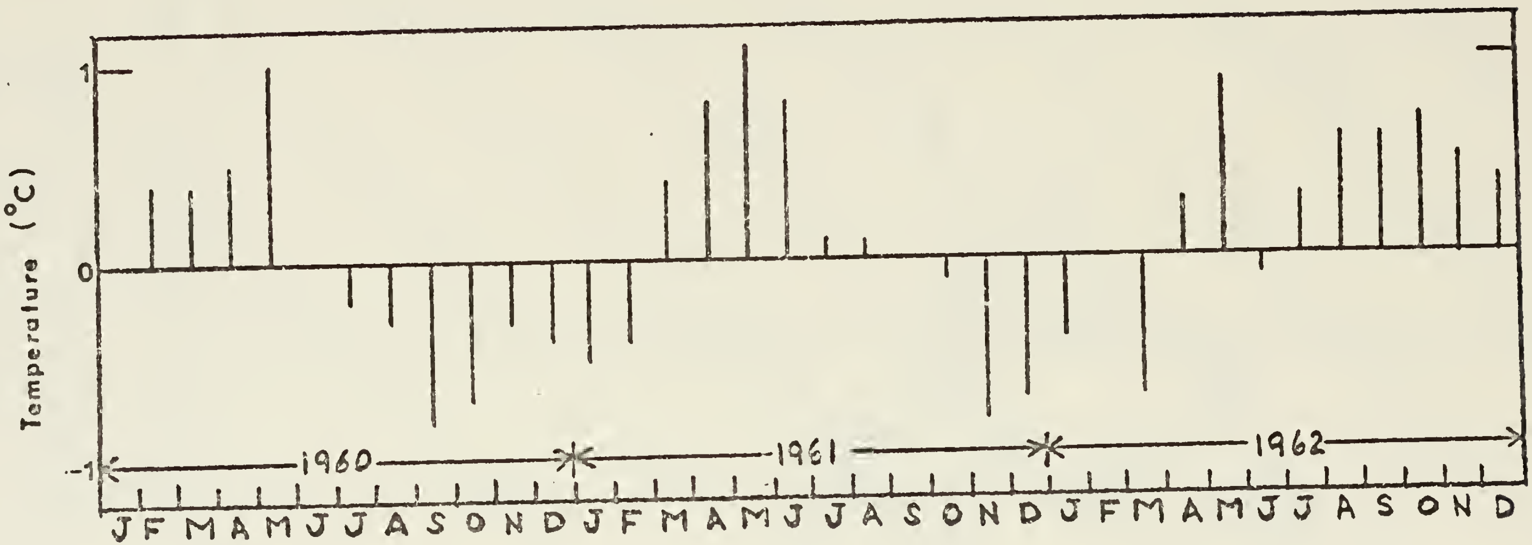

Figure 18: Monthly mean SST anomaly for 1960 and 1962. Positive values indicate higher temperatures than normal; negative values indicate lower temperatures than normal.

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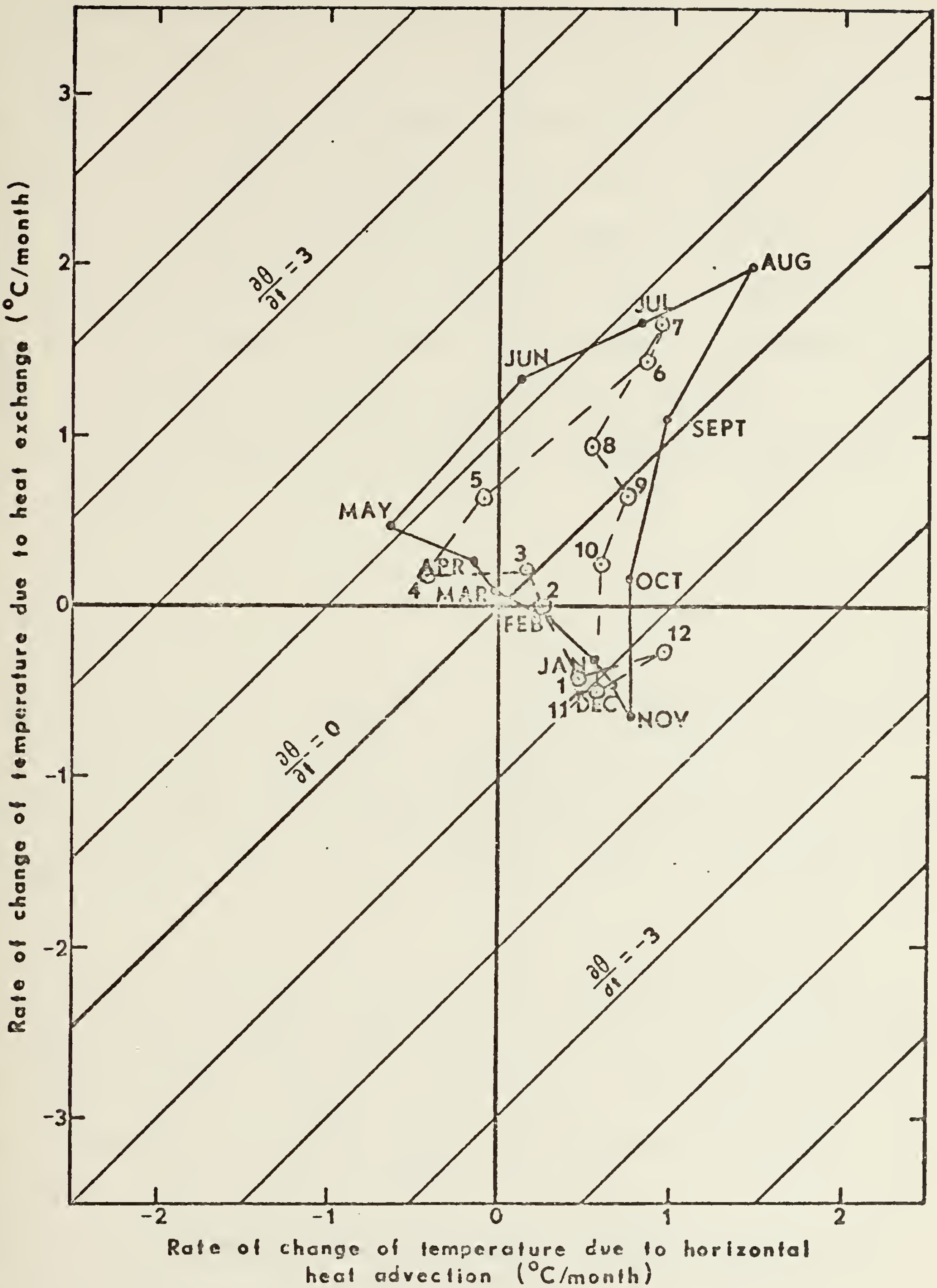

Figure 19: Observed variation of the monthly means for 1960 (broken line) at OWS NOVEMBER. (1 - Jan., 2 - Feb., etc.). The solid line represents the annual variation of the monthly means. Plus values indicate warming by heat exchange and cooling by advection.

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In February and March the observed rate of change of temperature indicated the cooling rate was more severe than normal. Increased cooling rates due to advection of cold water combined with a near normal heat exchange rate kept SSTs suppressed during this period (Figure 20).

Normally in April the observed rate of change of temperature is 0.4°C/month, but in 1962 it was approximately four times this value. This rapid temperature increase was almost entirely due to an abnormally large influx of warm water. Heating processes were at near normal levels in May, but the large heat gain during April elevated SSTs in May nearly 1°C above normal.

G. THE YEAR, 1967

Basically, 1967 was a warm year. Figure 21 shows a four month period (April through July) when the SST registered below normal values. Commencing in August and continuing throughout the remainder of the year, the SST was above normal with the maximum anomaly of 1.7°C recorded in October.

Figure 22 shows three trends that occupy similar time increments as the annual long term monthly mean observed rate of change of temperature (Figure 12). In 1967, though, the magnitudes of the observed rates of change of temperature in July, August, and September substantially surpassed the normal rates of warming for those months. This increased warming rate was primarily the result of excess heat gained from the atmosphere, advection rates being near normal.

November experienced a rate of cooling almost twice as great as normally encountered. Loss of heat to the atmosphere at twice the normal rate accounted for most of this. The SST remained above normal, however,

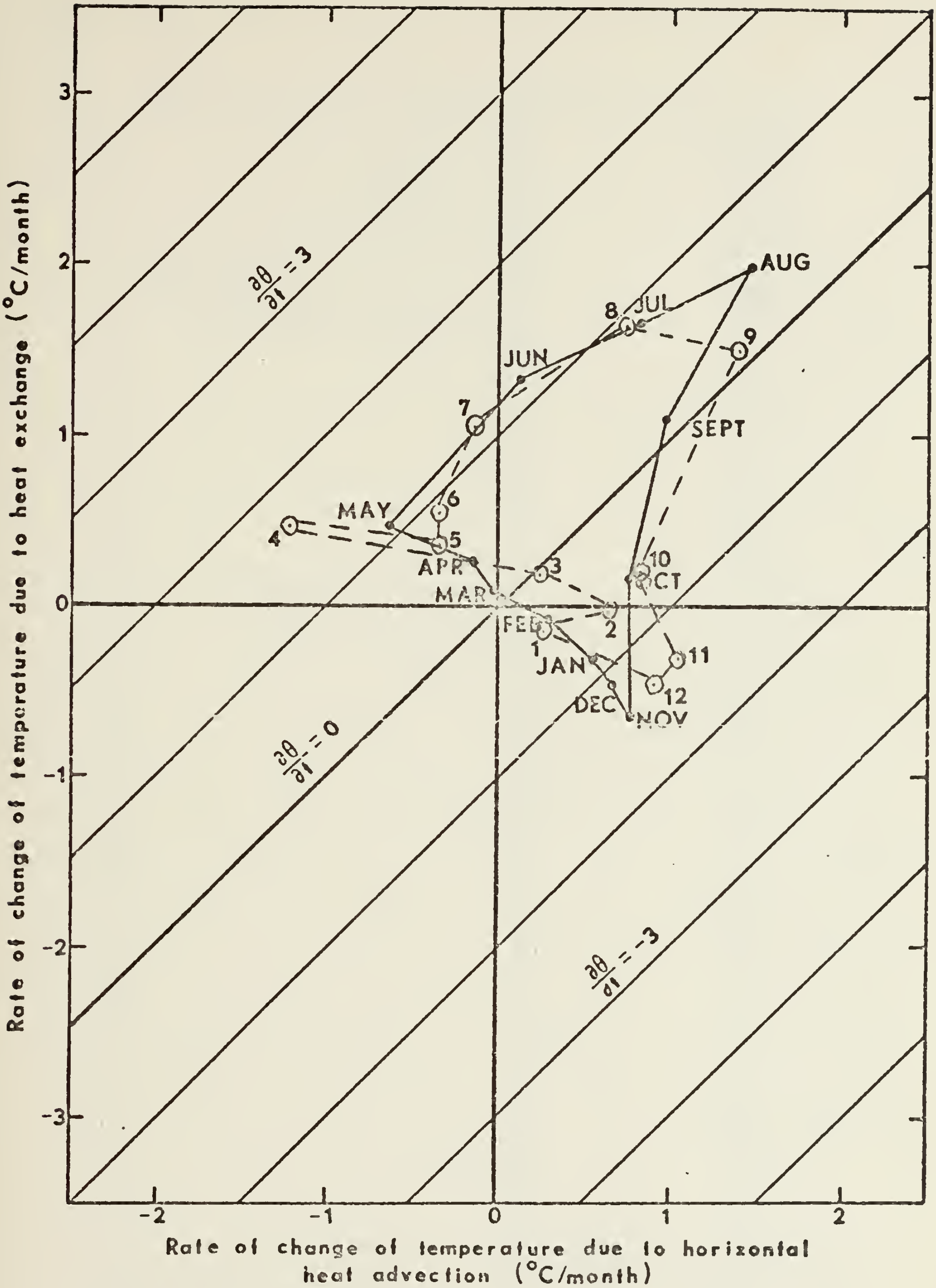

Figure 20: Observed variation of the monthly means for 1962 (broken line) at OWS NOVEMBER. (1 - Jan., 2 - Feb., etc.). The solid line represents the annual variation of the monthly means. Plus values indicate warming by heat exchange and cooling by advection.

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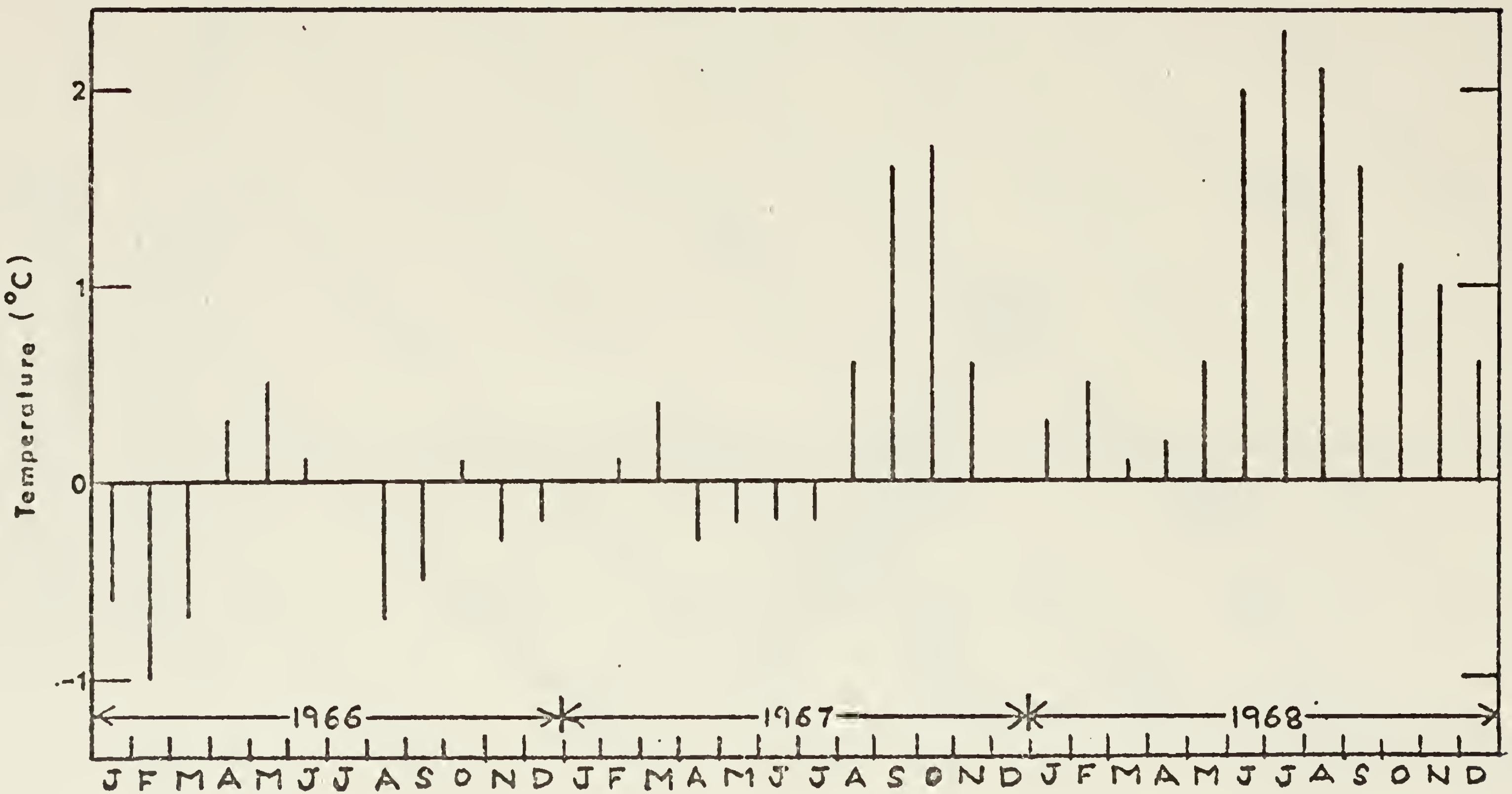

Figure 21: Monthly mean SST anomaly for 1967 and 1968. Positive values indicate higher temperatures than normal; negative values indicate lower temperatures than normal.

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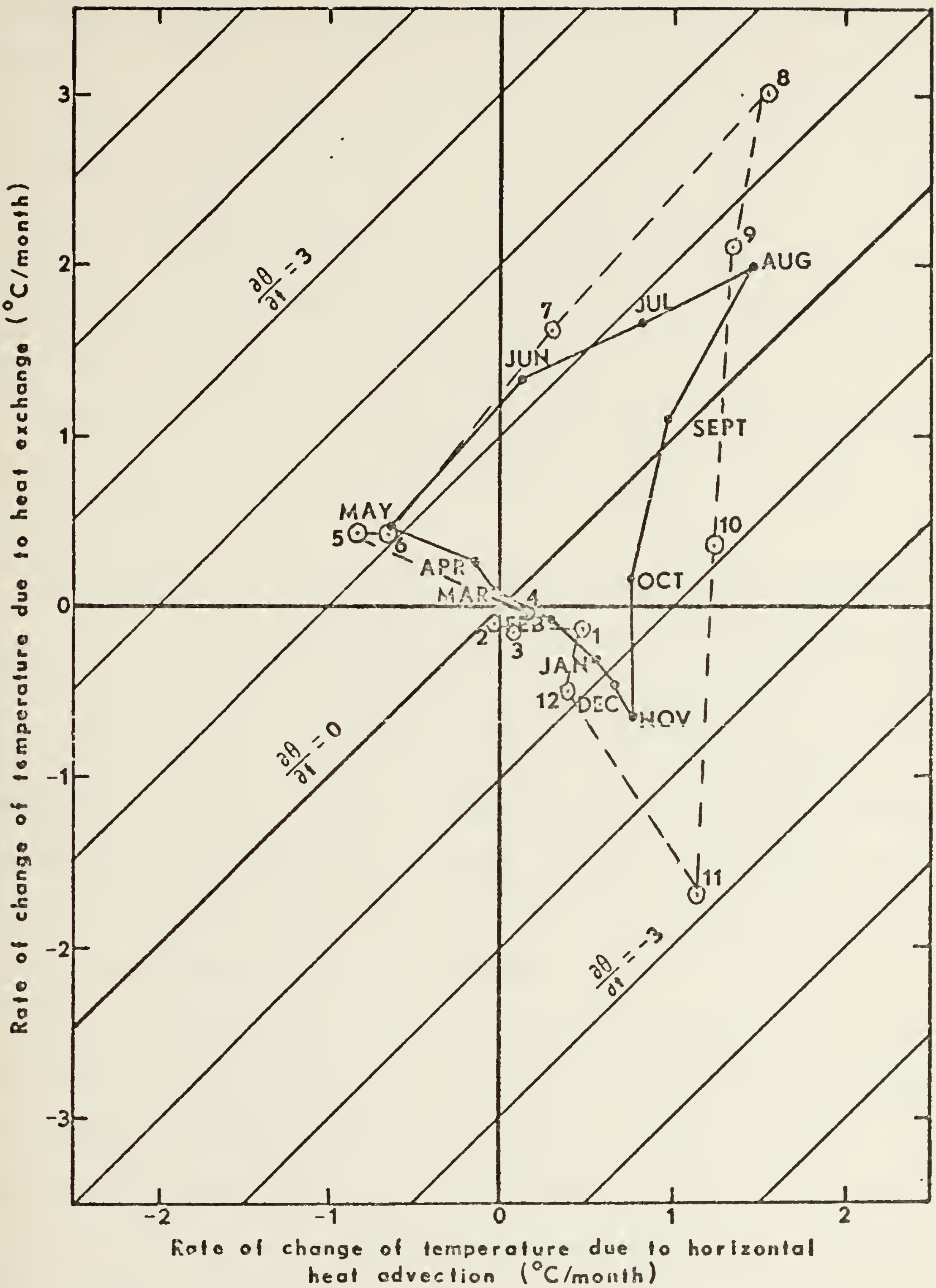

Figure 22: Observed variation of the monthly means for 1967 (broken line) at OWS NOVEMBER. (1 - Jan., 2 - Feb., etc.). The solid line represents the annual variation of the monthly means. Plus values indicate warming by heat exchange and cooling by advection.

because of the large heat anomalies required in the preceding three months.

H. THE YEAR, 1968

Above normal SST prevailed throughout all of 1968 resulting in one of the warmest years in the seventeen year period studied. A maximum SST of 2.3°C occurred during July (Figure 21).

Figure 23 also exhibits three trends that occupy similar time increments as the annual long term monthly mean observed rate of change of temperature (Figure 12).

During May and June the SST increased at approximately 2°C/month--nearly twice the normally occurring rate. During this time the observed steady increase in SST is caused primarily by the constantly increasing heat content added at the sea surface and to some extent in May by an increased advection rate. For the remainder of the summer the sustained high SST anomaly is maintained by slightly higher heat exchange rates. The SST anomalies may have even been higher except for the moderating effect of increased rates of cold advection.

As previously mentioned, Namias [1971] noted an anomalous warming in the southern portion of the NPO in May and June, 1968. At OWS NOVEMBER he attributed one-third of the warming to heat exchange, exclusive of advection and mixing. The remaining two-thirds of the heating apparently resulted from the inward advection and downwelling of insolation heated surface water.

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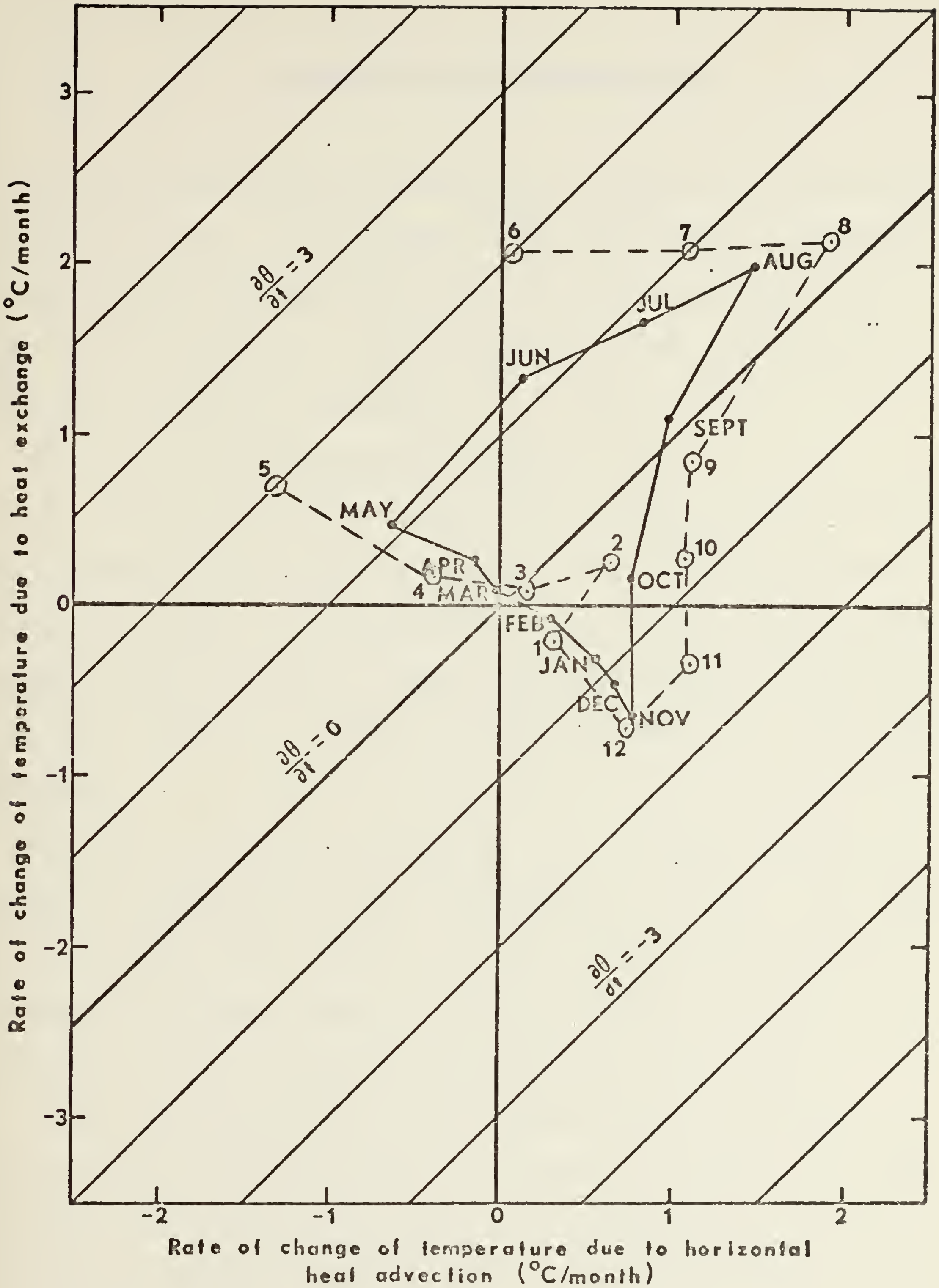

Figure 23: Observed variation of the monthly means for 1968 (broken line) at OWS NOVEMBER. (1 - Jan., 2 - Feb., etc.). The solid line represents the annual variation of the monthly means. Plus values indicate warming by heat exchange and cooling by advection.

V. CONCLUSIONS AND RECOMMENDATIONS

This study investigated the effects of horizontal heat advection and heat exchange across the sea surface on the observed rate of change of temperature at OWS NOVEMBER (30N 140W) from 1954 through 1970. An approach to a cause-effect relationship with each individual process evaluated separately was undertaken.

The results of this research show that:

1. Three distinct trends in the seasonal variations of the observed rate of change of temperature as affected by heat advection and heat exchange are present. A combination of heat advection and heat exchange prevailed in the first (May - August) and third (November - May) trends, while heat exchange was the dominant process in the second trend (August - November).

2. In the first trend the observed rate of change of temperature increases at the constant rate of approximately $1^{o}C$/month. During this time the observed steady increase in SST is caused by the constantly increasing heat content added at the sea surface but its rate of increase is moderated by the constantly increasing influx of cool water.

3. In the second trend the SST initially experiences a gradual increase until the peak temperature is reached in September. Then the SST begins to decrease and the observed rate of cooling steadily increases. Advection of cold water is present but at a relatively constant value of approximately $0.8^{o}C$/month. The major reason for the decline in the SST during this period is that, although the sea is receiving more heat than it is giving off, the rate at which it receives heat steadily decreases.

4. In the third trend the SST continues to gradually decline at a slower rate until the minimum SST of 18.2°C is reached in March. The rate of heat lost from the ocean and the rate of advection of cold water steadily diminish until March when they are near zero. A gradual increase in SST then ensues in April and May corresponding to steadily increasing rates of warm advection and heat exchange with the rate of warming due to advection exceeding heat exchange in May.

5. Over short periods of time (month to month) the inception of anomalous SST patterns appears to be caused primarily by influxes of warm or cold water. The only exceptions to the dominance of abnormal influxes of warm or cold water over short periods occurred in the summer of 1967 and spring of 1968 when anomalous rates of heat gain from the atmosphere occurred to cause the above normal SSTs. Namias [1971], in corroboration with the conclusion of a dominance of heat exchange in May and June, 1968, attributed the overall warming to the development and maintenance of a strong and deep Pacific anti-cyclone in June with its center located near OWS NOVEMBER.

This study revealed that over short periods of time advection patterns were a very important process at OWS NOVEMBER. It is recommended that this study be used as a basis for the study of correlations between salinity and advection patterns (cold and warm). One avenue available for this type of study would be the application of Seckel's [1962] salt budget equation using the processes of water exchange across the sea surface and salt advection.

Another recommendation for future work is to determine what factors were responsible for the anomalous rates of heat exchange and advection, e.g. increased rates of insolation due to decreased cloud coverage,

increased persistence and intensity of atmospheric pressure cells such as the North Pacific High.

APPENDIX A

The characteristic advection diagram for OWS NOVEMBER and anomalous bar graphs of the three terms in the simplified temperature change equation are presented. The charts cover the years 1954 - 1970 and are divided into three year increments. The order of presentation in the three year increments are:

a. characteristic advection diagram

b. monthly mean anomaly in observed rate of SST

c. monthly mean anomaly in SST change attributed to horizontal advection

d. monthly mean anomaly in SST change attributed to heat exchange at the sea surface

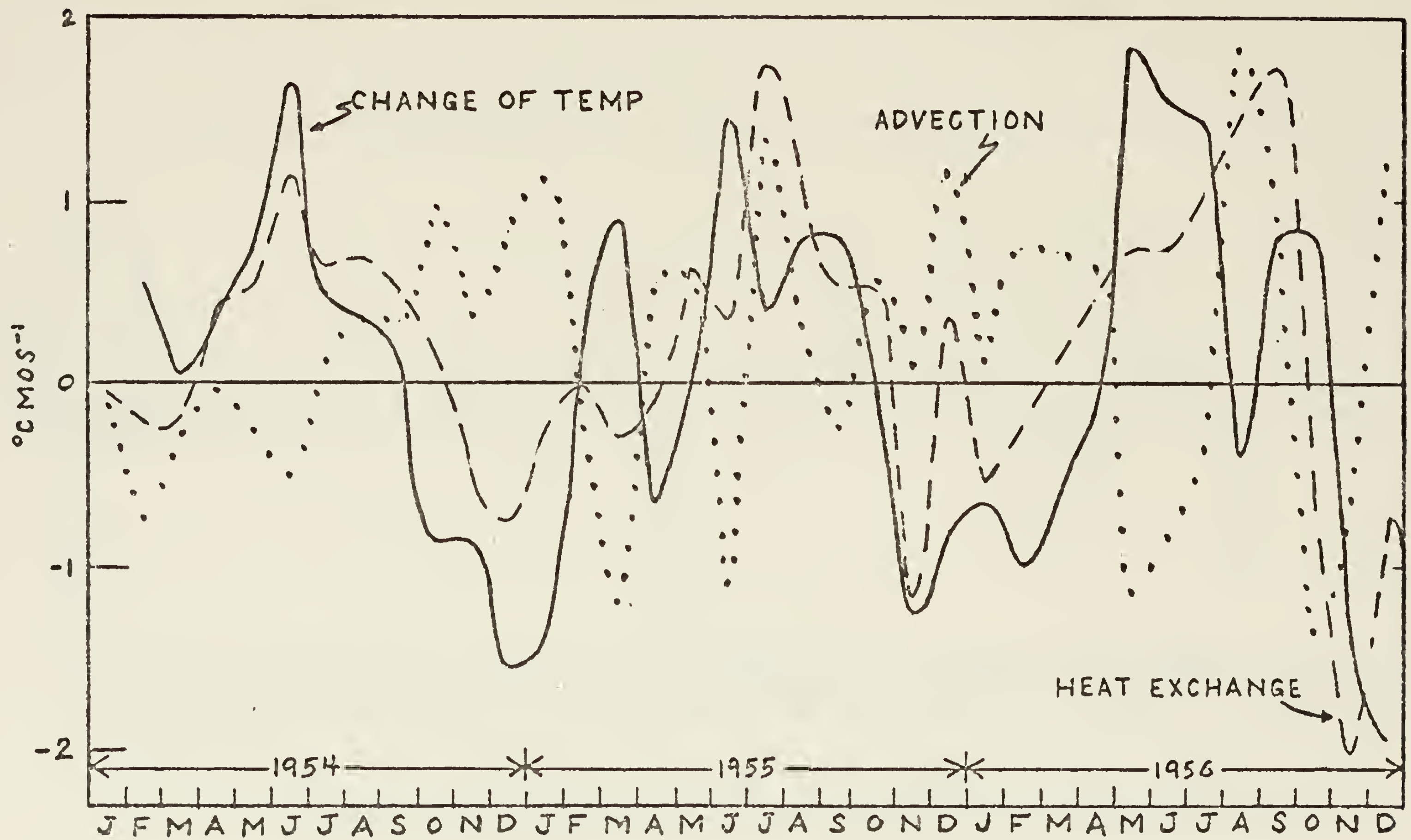

Figure Ala: Characteristic advection diagram representing variations of monthly means at OWS NOVEMBER.

Figure A1b: Monthly mean anomaly in observed rate of change of SST. Positive values indicate a period when the rate of warming is greater than the long-term mean for this period.

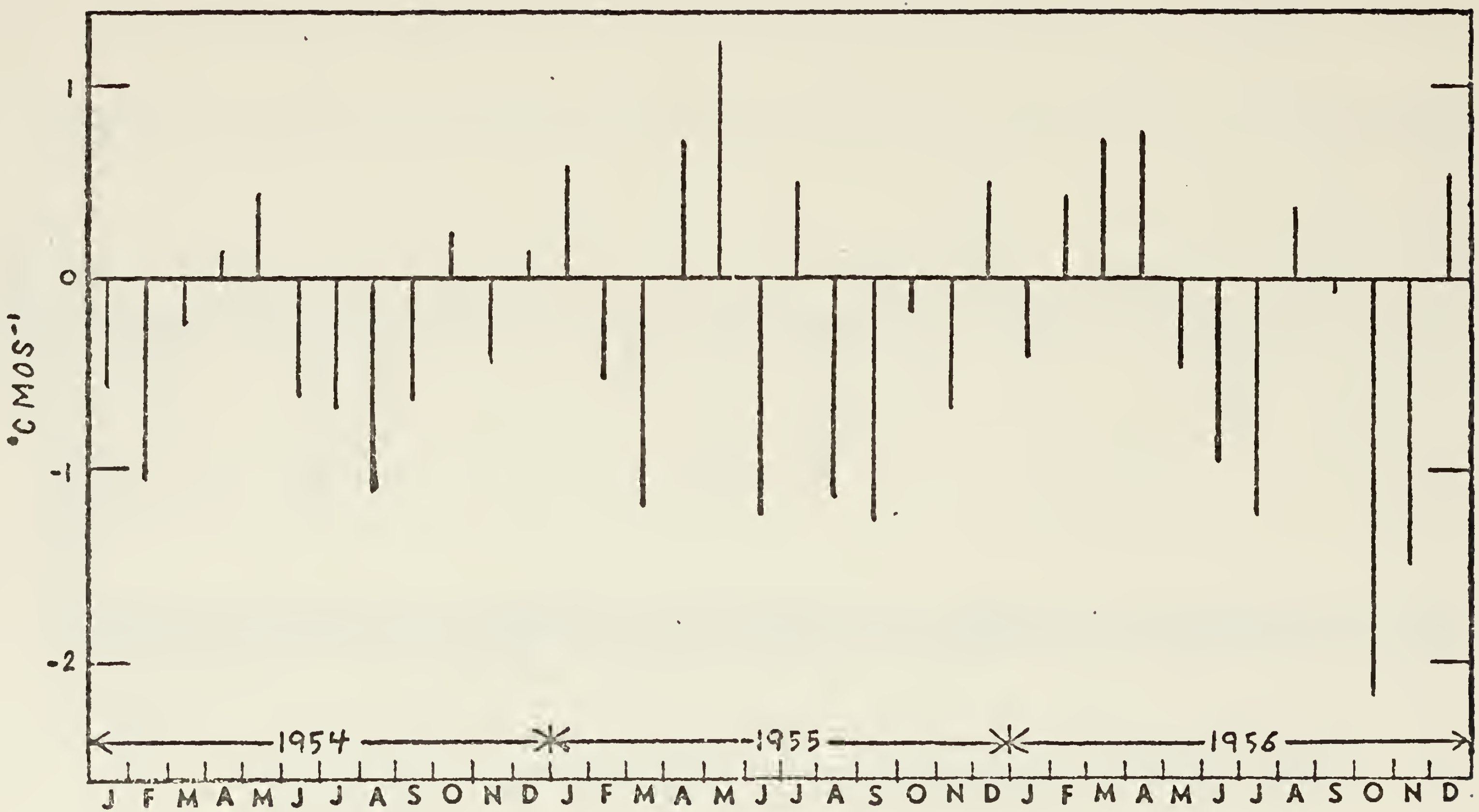

Figure Alc: Monthly mean anomaly in SST change attributed to horizontal advection. Positive values indicate a period when colder advection is greater than the long-term mean for this period.

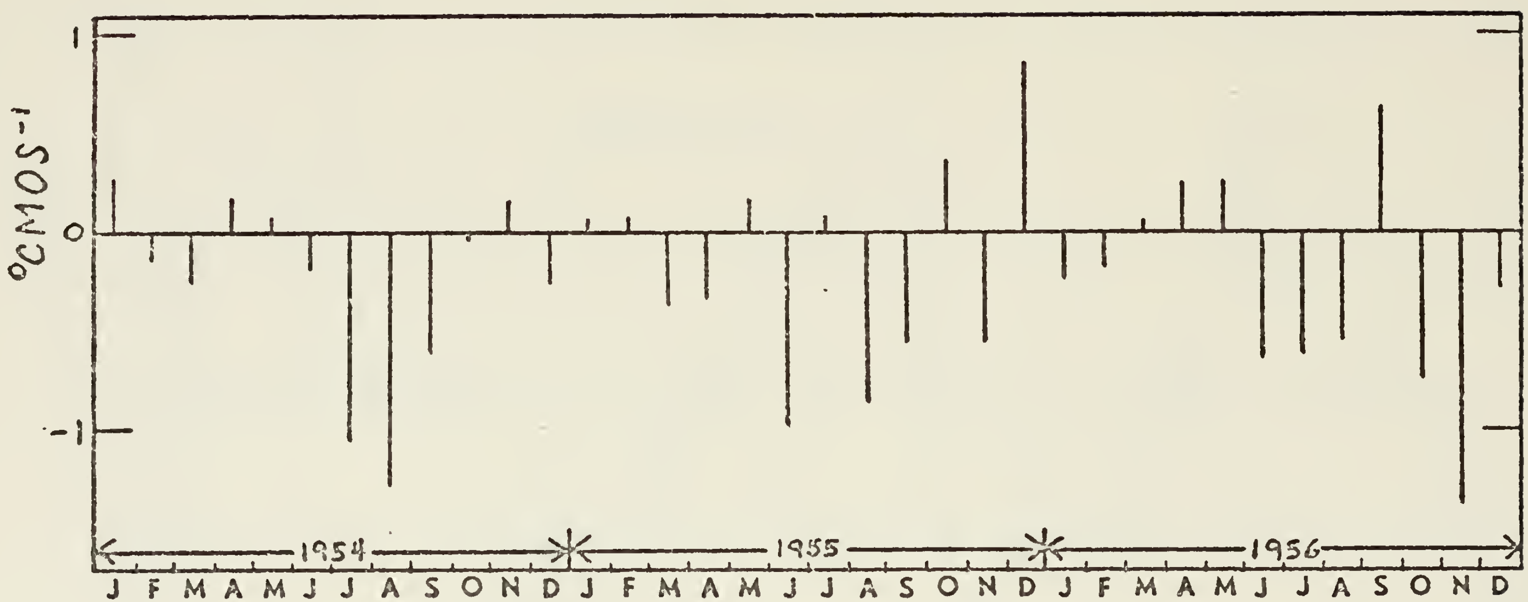

Figure Ald: Monthly mean anomaly in SST change attributed to heat exchange at the sea surface. Positive values indicate periods where the sea surface receives more heat from the atmosphere than normally expected for this period.

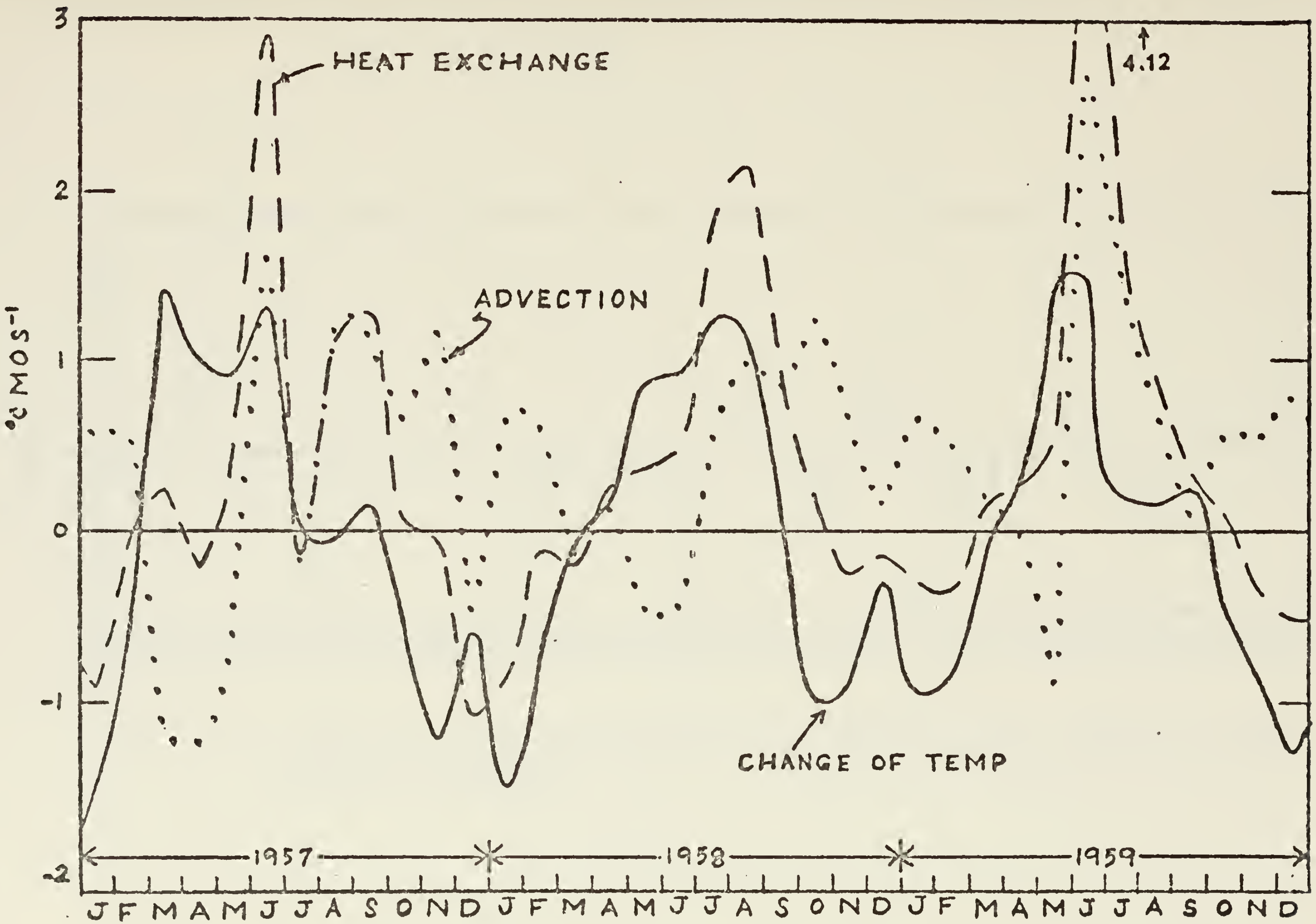

Figure A2a: Characteristic advection diagram representing variations of monthly means at OWS NOVEMBER.

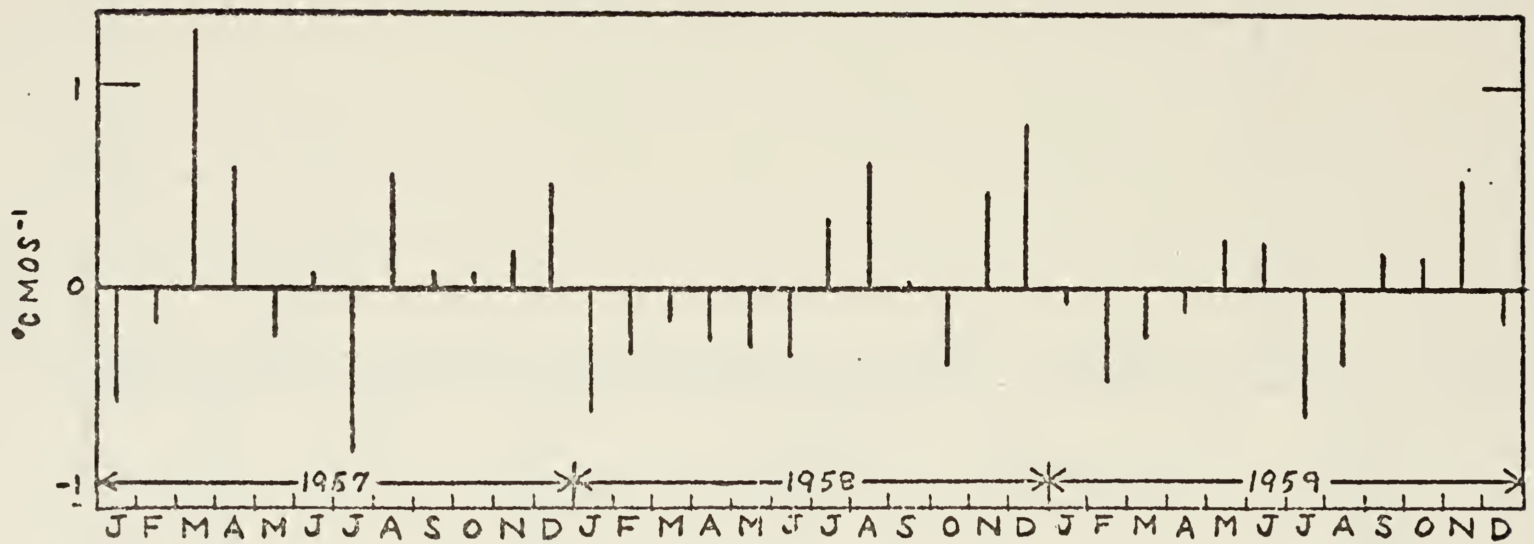

Figure A2b: Monthly mean anomaly in obervad rate of change of SST. Positive values indicate a period when the rate of warming is greater than the long-term mean for this period.

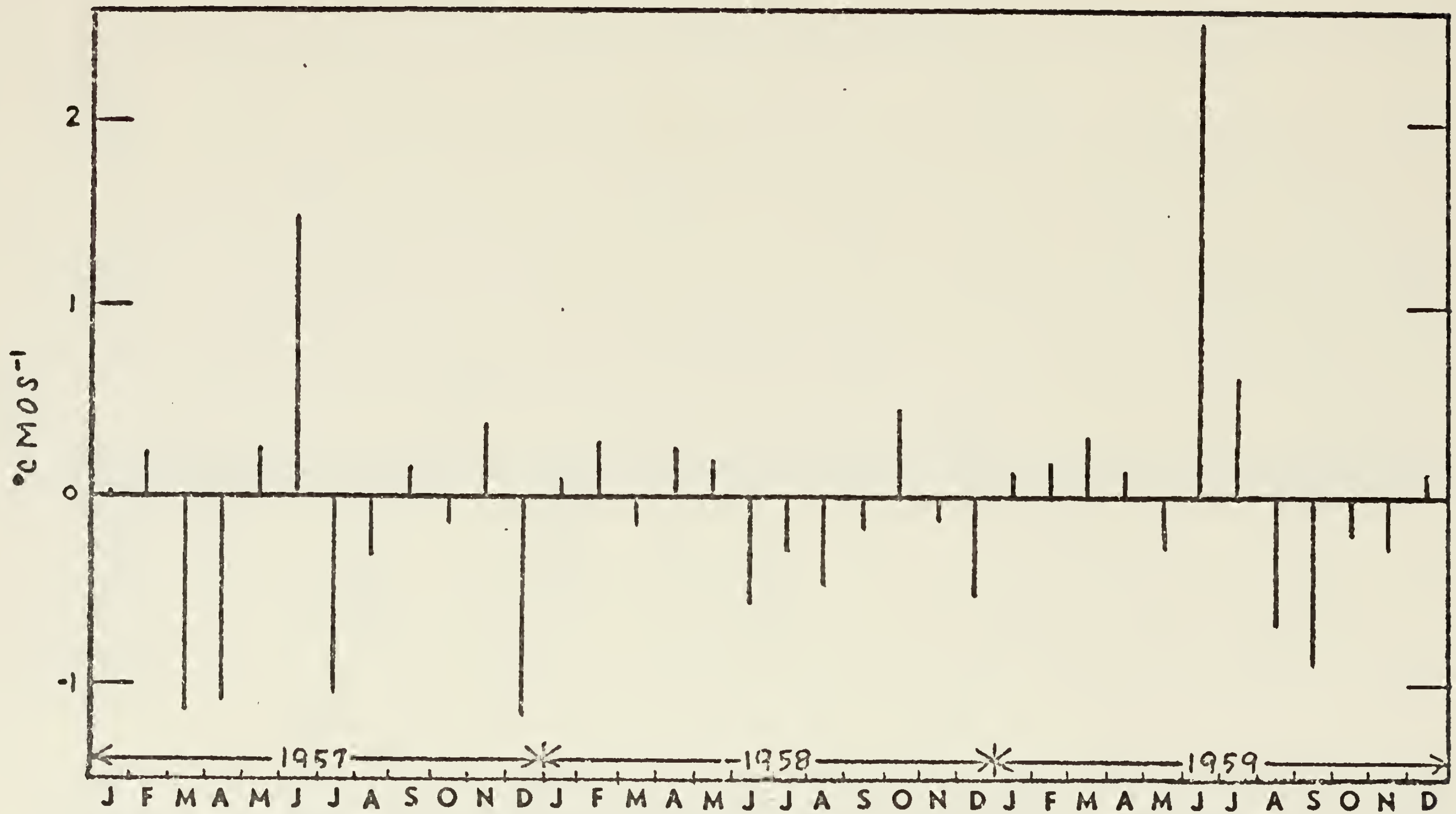

Figure A2c: Monthly mean anomaly in SST change attributed to horizontal advection. Positive values indicate a period when cooler advection is greater than the long-term mean for this period.

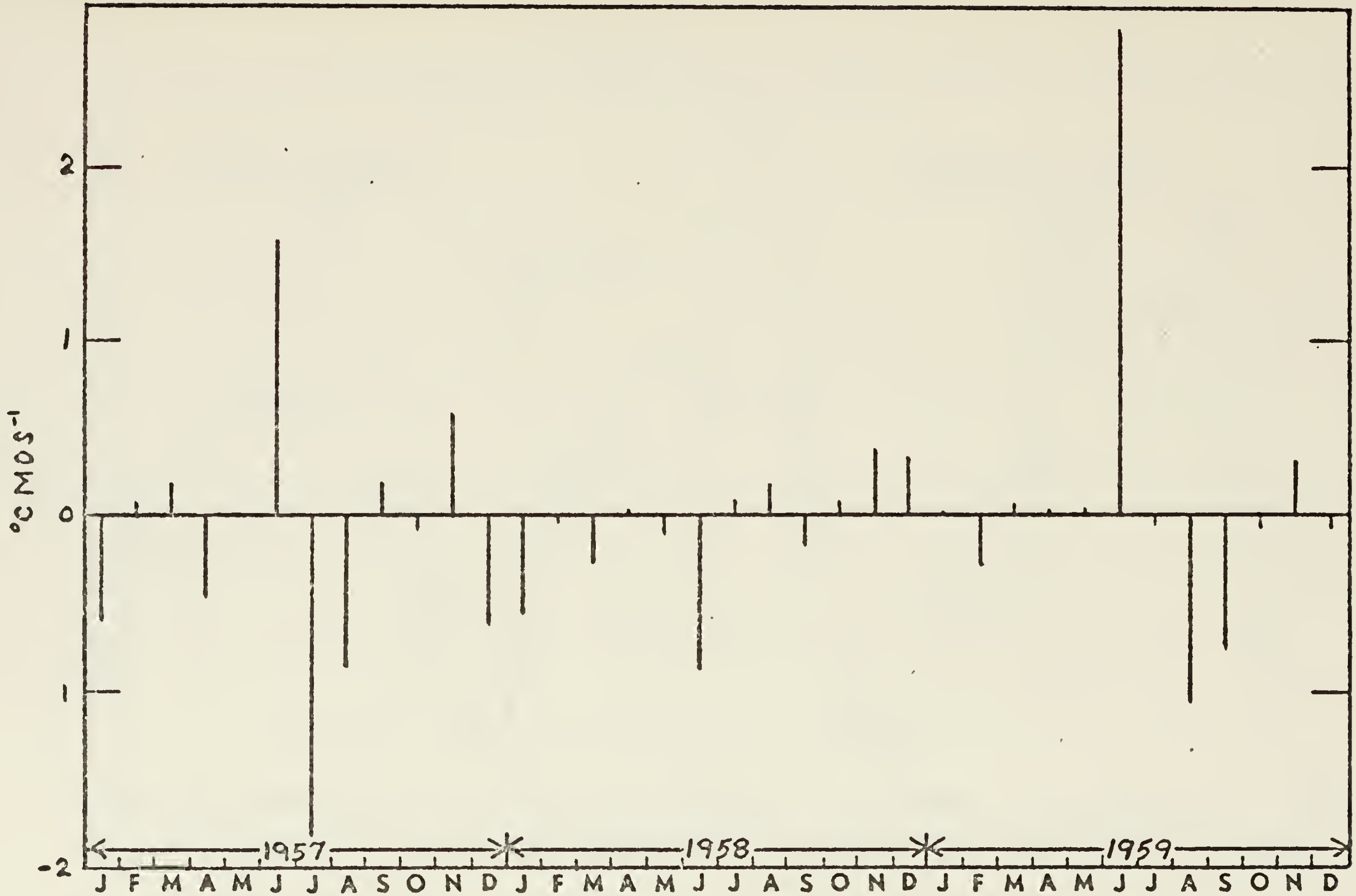

Figure A2d: Monthly mean anomaly in SST change attributed to heat exchange at the sea surface. Positive values indicate periods where the sea surface receives more heat from the atmosphere than normally expected for this period.

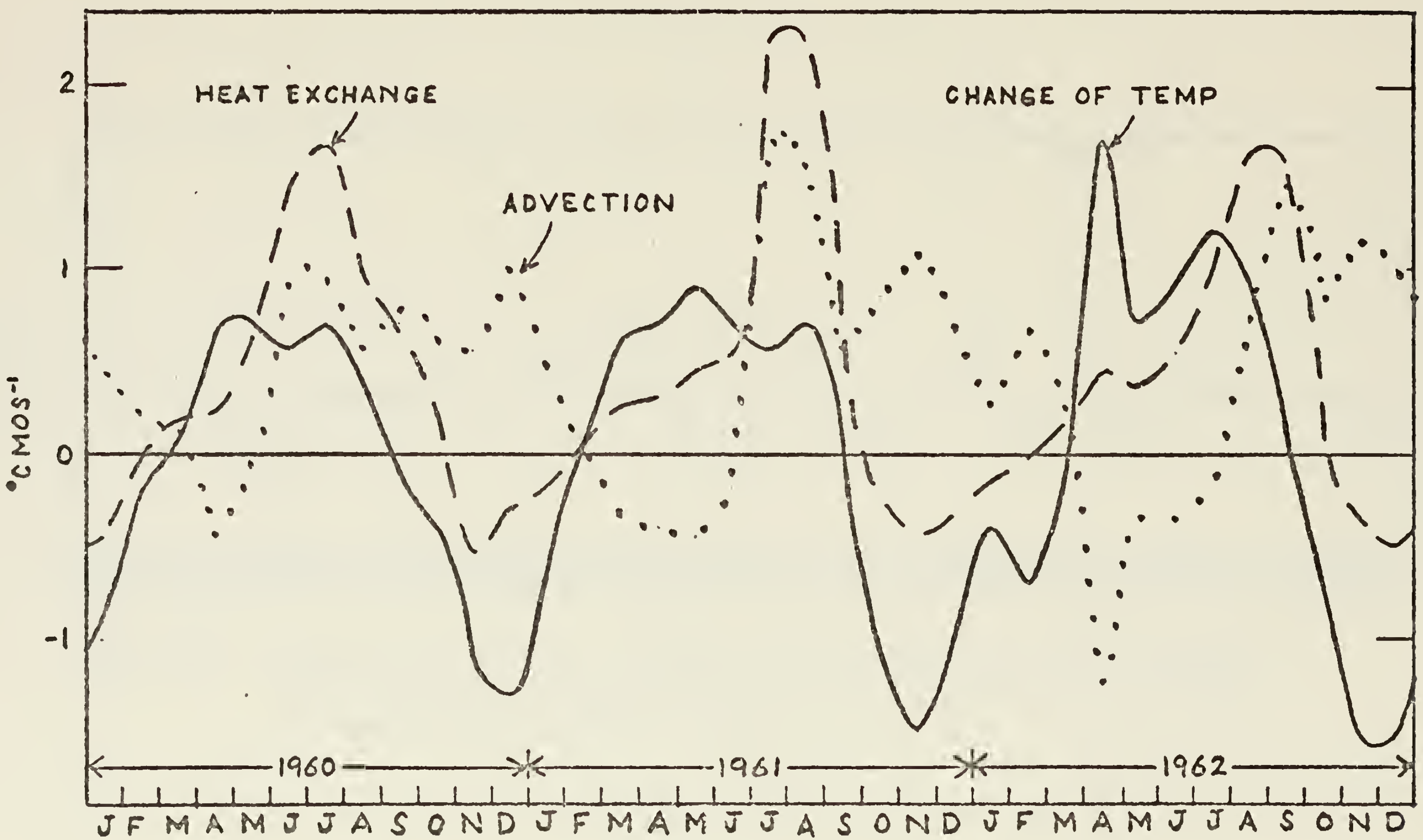

Figure A3a: Characteristic advection diagram representing variations of monthly means at OWS NOVEMBER.

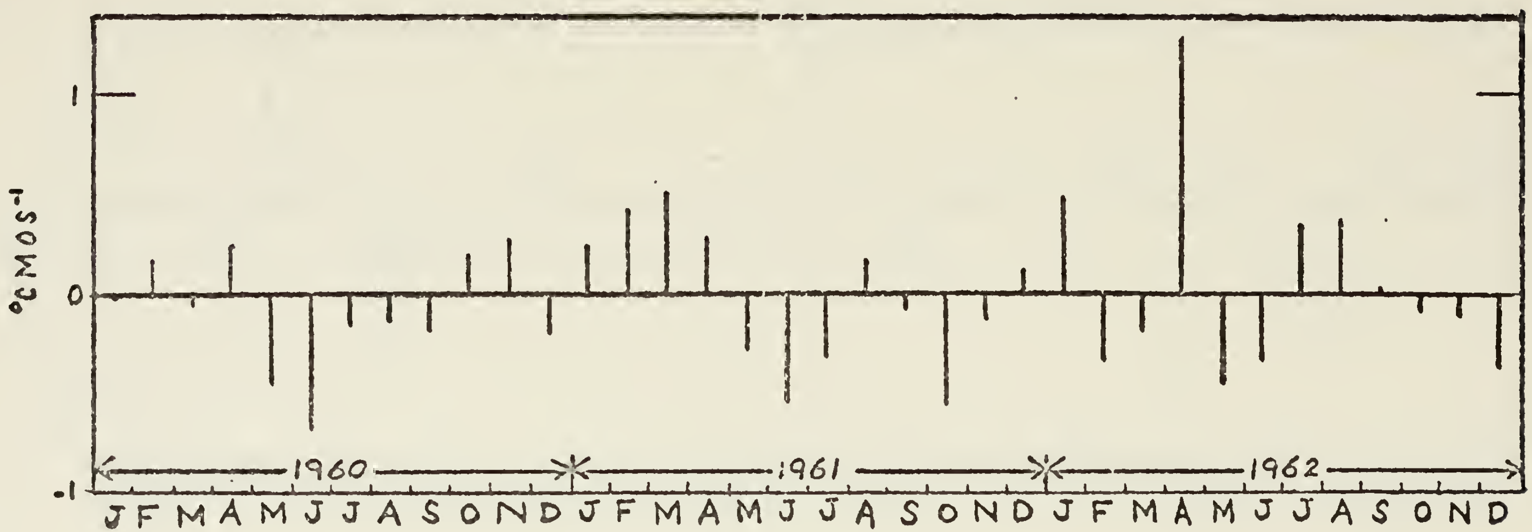

Figure A3b: Monthly mean anomaly in observed rate of change of SST. Positive values indicate a period when the rate of warming is greater than the long-term mean for this period.

Figure A3c: Monthly mean anomaly in SST change attributed to horizontal advection. Positive values indicate a period when cooler advection is greater than the long-term mean for this period.

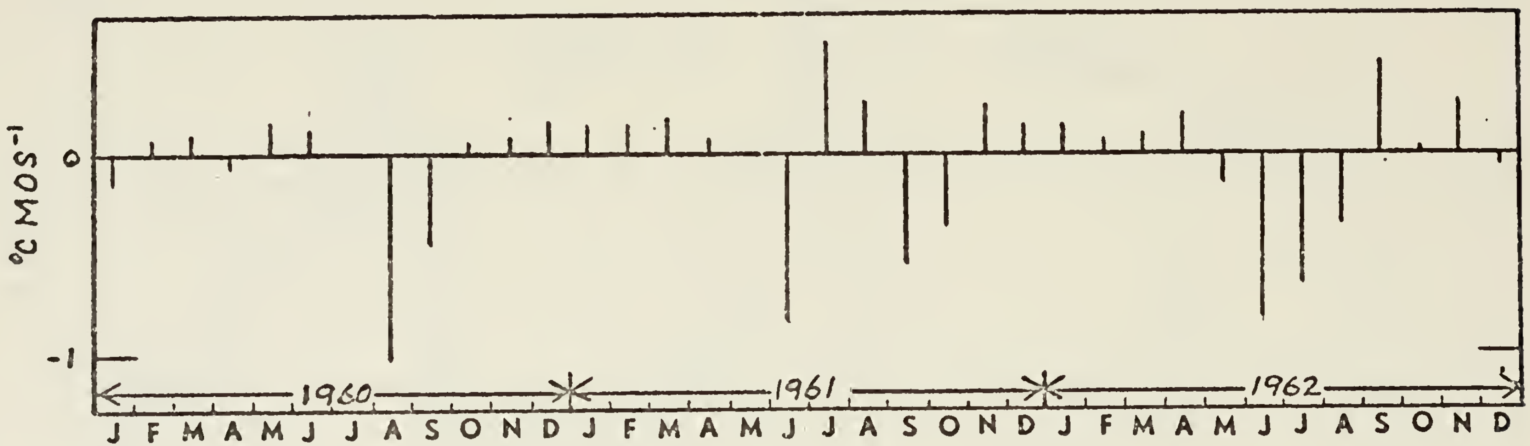

Figure A3d: Monthly mean anomaly in SST change attributed to heat exchange at the sea surface. Positive values indicate periods where the sea surface receives more heat from the atmosphere than normally expected for this period.

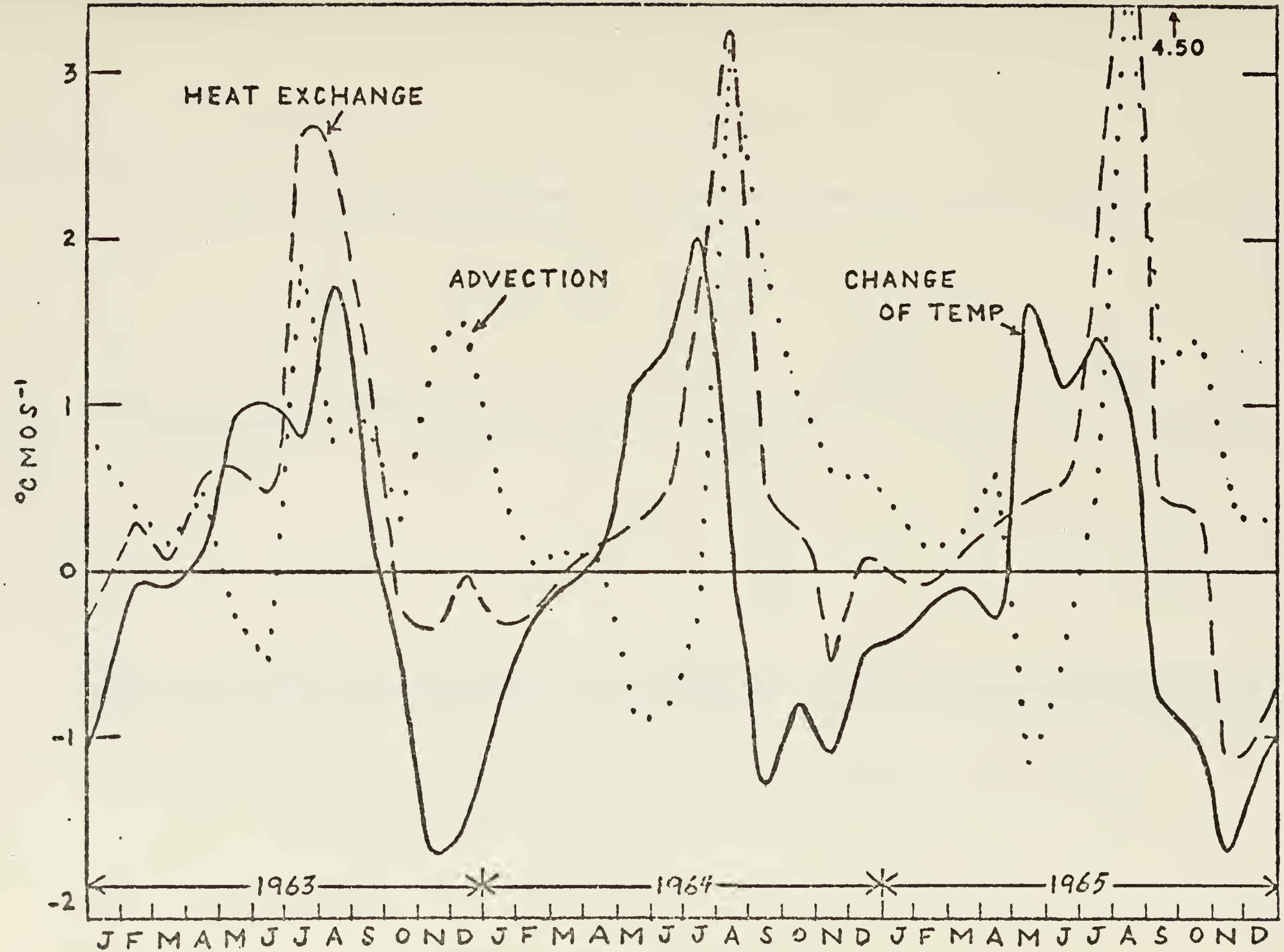

Figure A4a: Characteristic advection diagram representing variations of monthly means at CWS NOVEMBER.

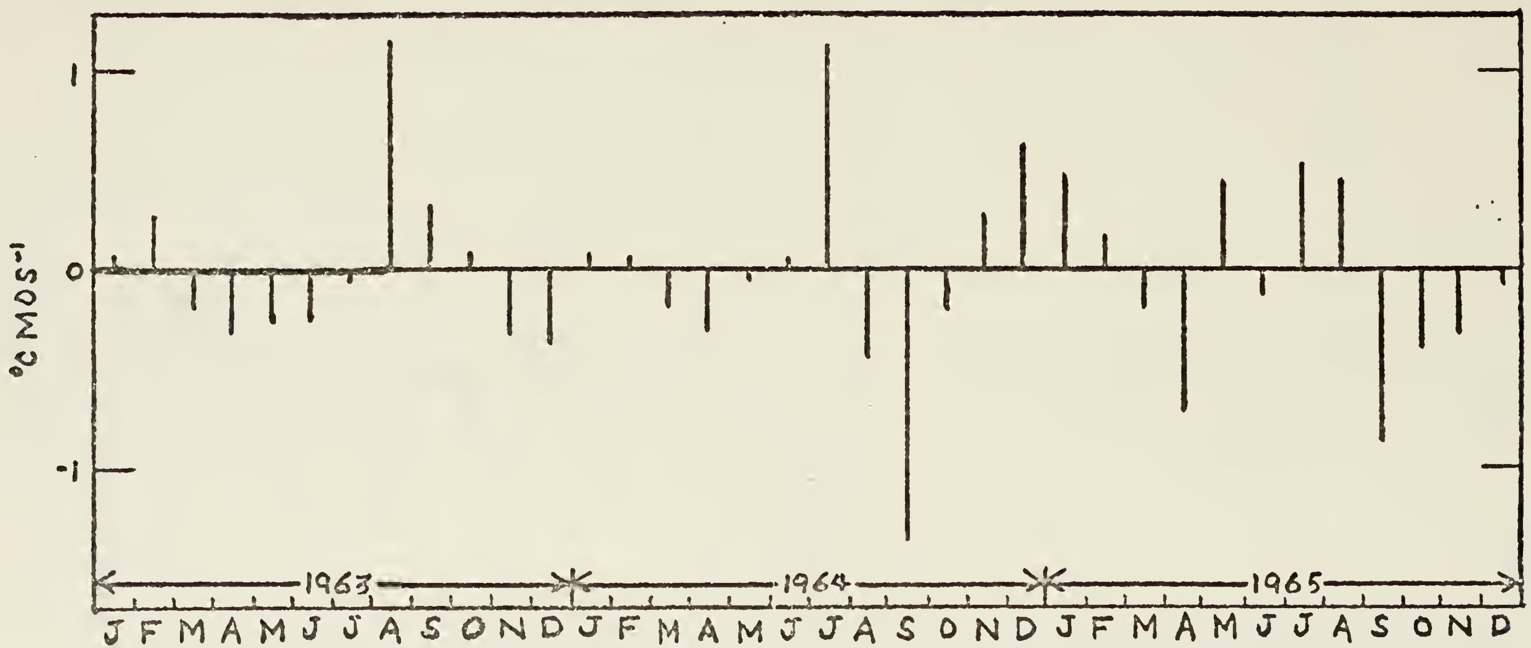

Figure A4b: Monthly mean anomaly in observed rate of change of SST. Positive values indicate a period when the rate of warming is greater than the long-term mean for this period.

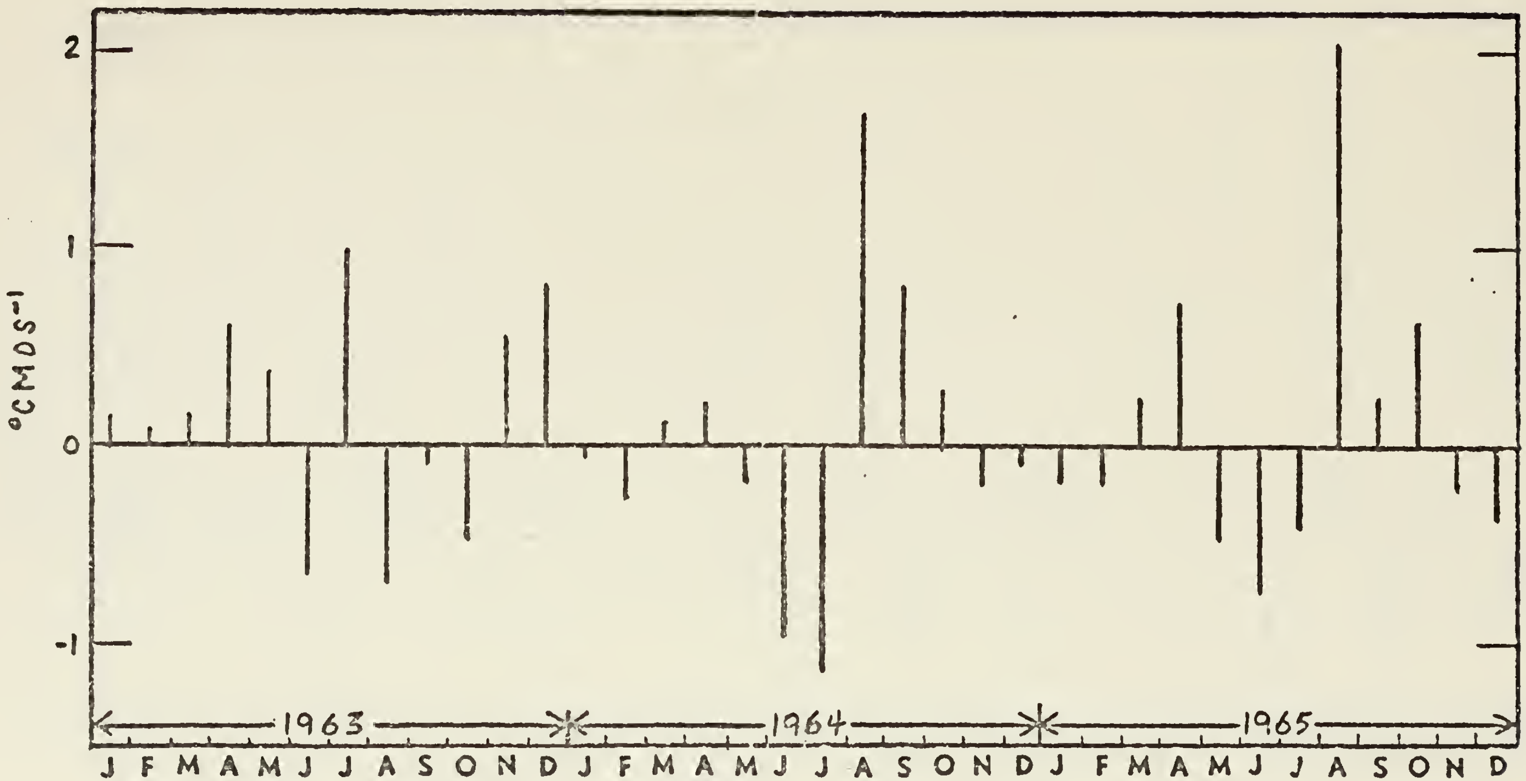

Figure A4c: Monthly mean anomaly in SST change attributed to horizontal advection. Positive values indicate a period when colder advection is greater than the long-term mean for this period.

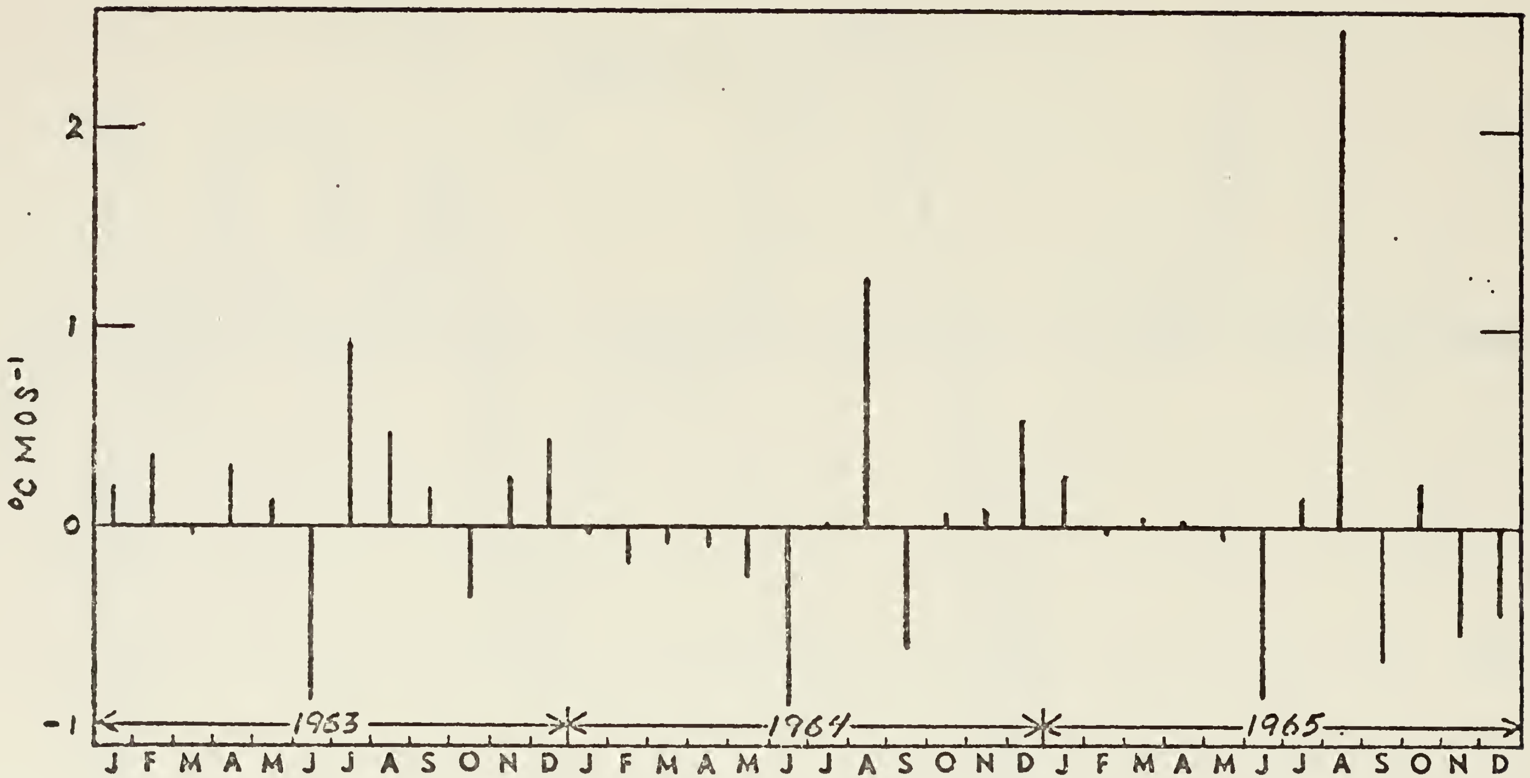

Figure A4d: Monthly mean anomaly in SST change attributed to heat exchange at the sea surface. Positive values indicate periods where the sea surface receives more heat from the atmosphere than normally expected for this period.

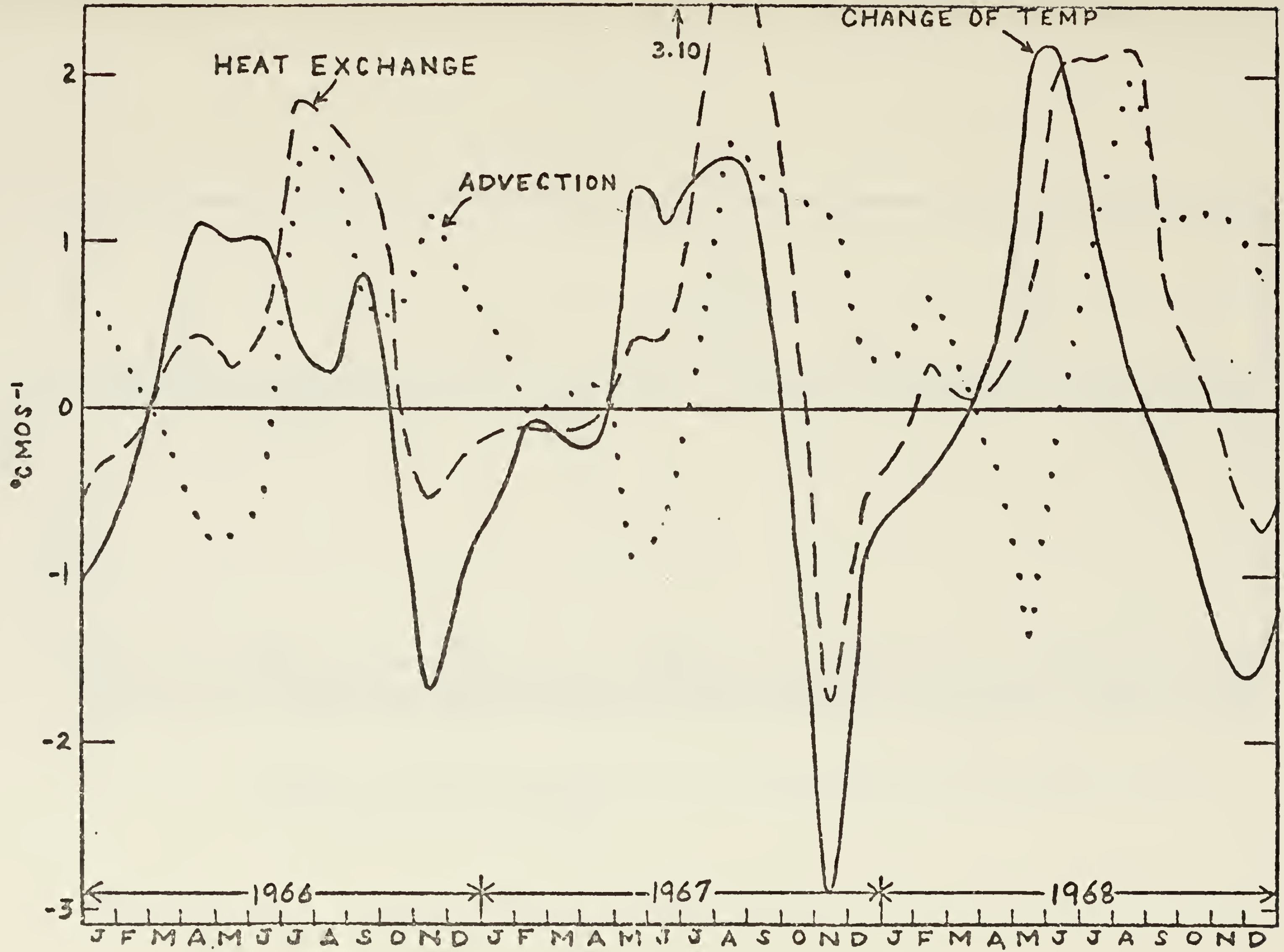

Figure A5a: Characteristic advection diagram representing variations of monthly means at OWS NOVEMBER.

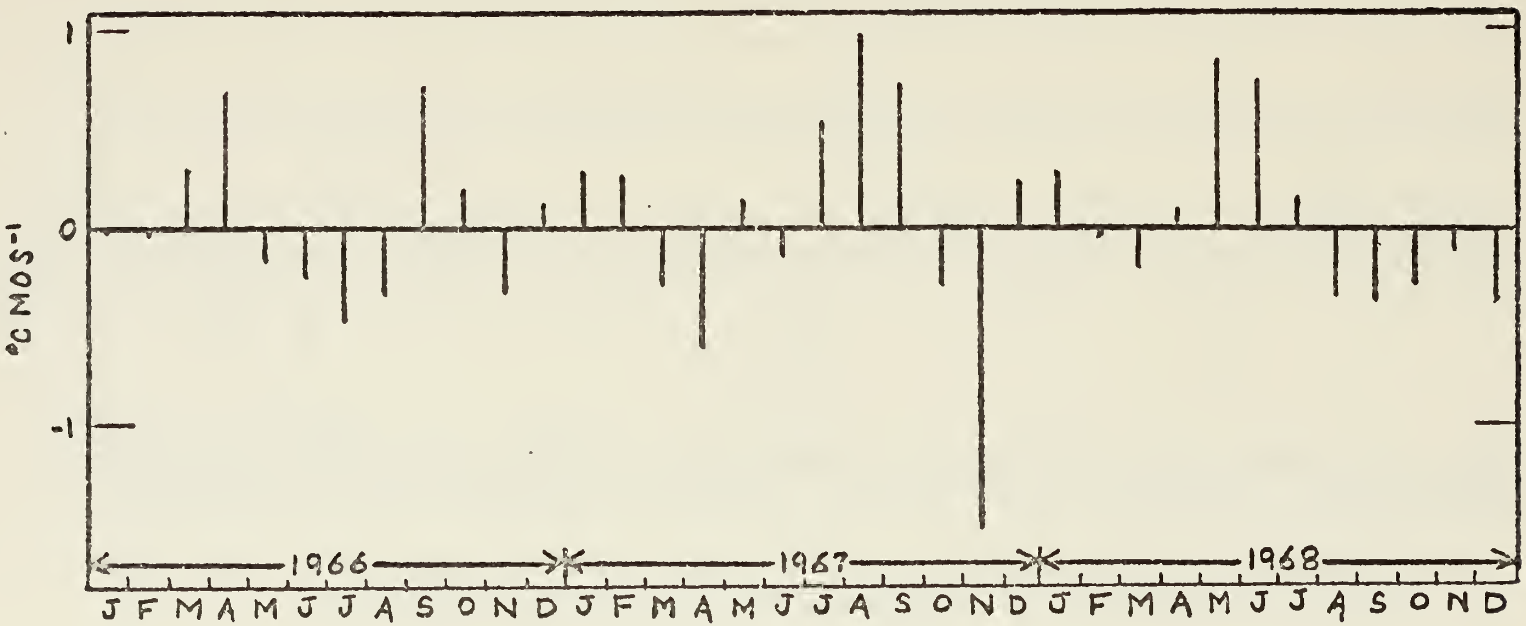

Figure A5b: Monthly mean anomaly in observed rate of change of SST. Positive values indicate a period when the rate of warming is greater than the long-term mean for this period.

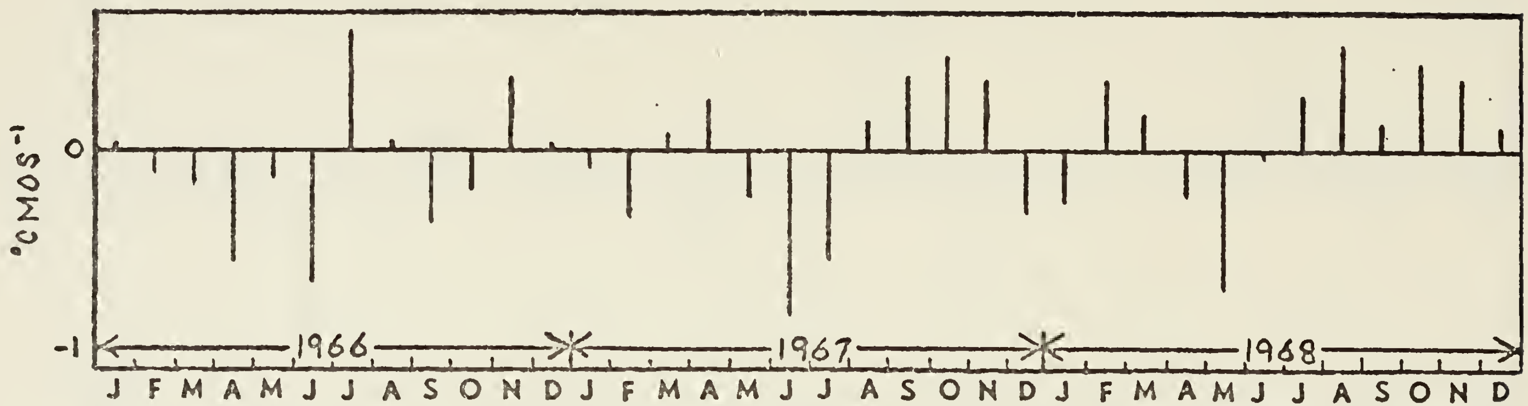

Figure A5c: Monthly mean anomaly in SST change attributed to horizontal advection. Positive values indicate a period when cooler advection is greater than the long-term mean for this period.

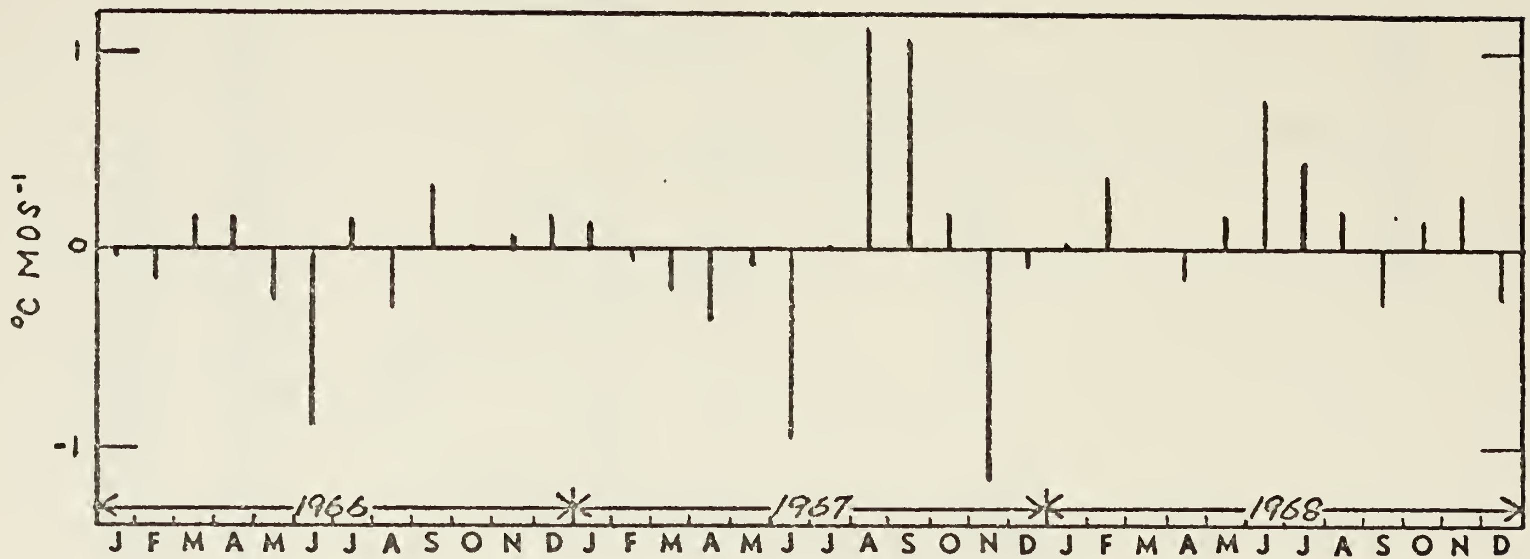

Figure A5d: Monthly mean anomaly in SST change attributed to heat exchange at the sea surface. Positive values indicate periods where the sea surface receives more heat from the atmosphere than normally expected for this period.

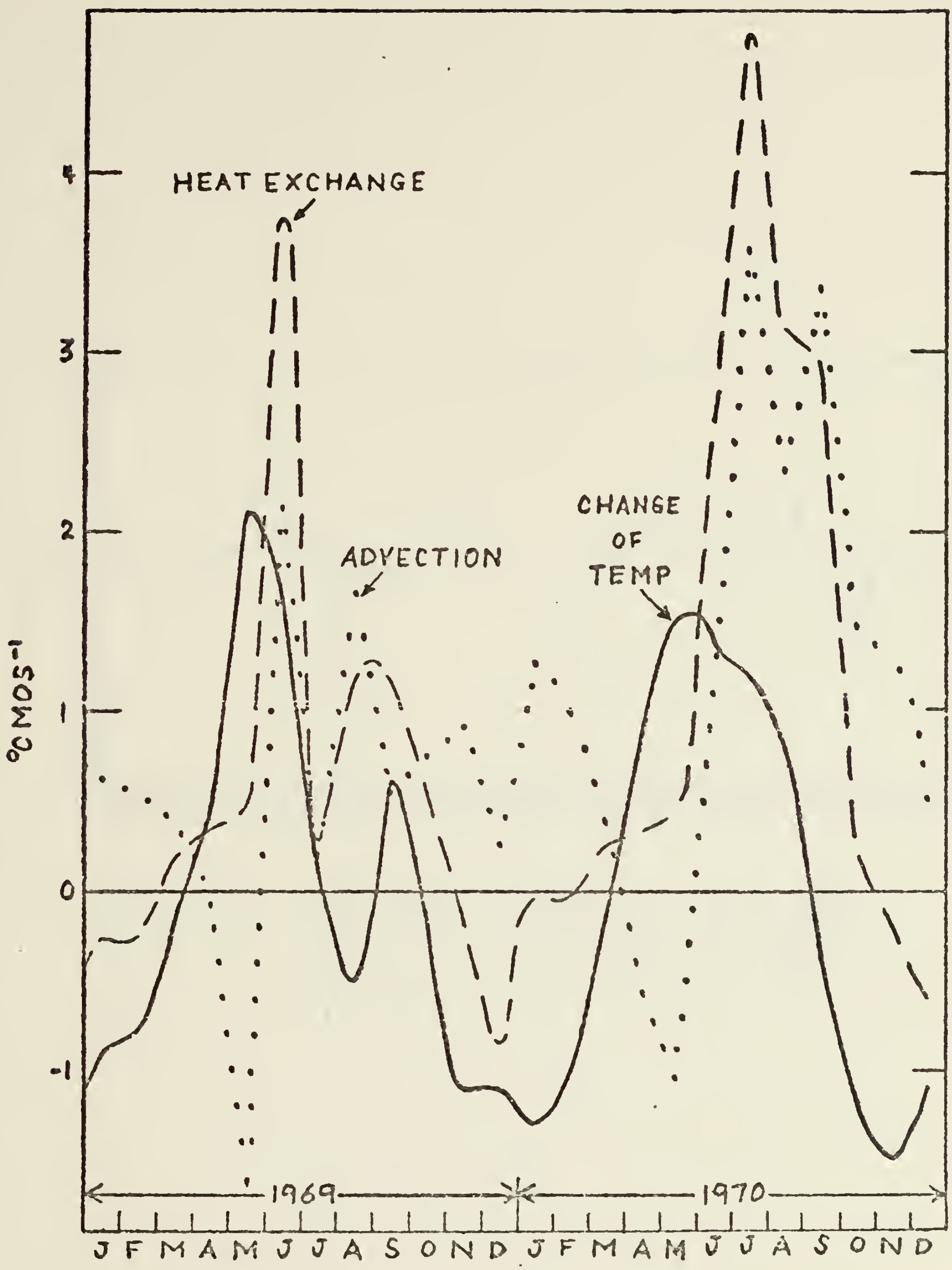

Figure A6a: Characteristic advection diagram representing variations of monthly means at OWS NOVEMBER.

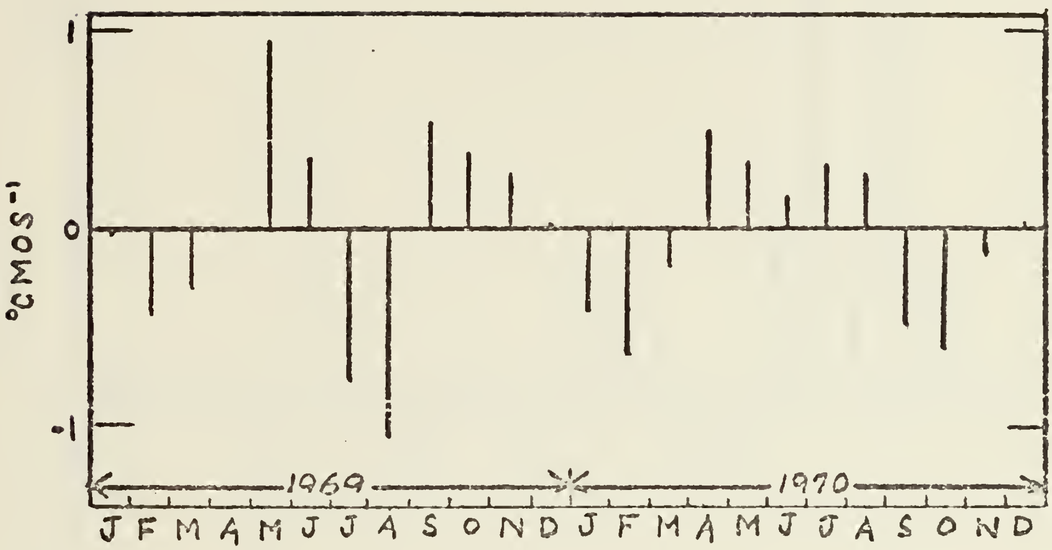

Figure A6b: Monthly mean anomaly in observed rate of change of SST. Positive values indicate a period when the rate of warming is greater than the long-term mean for this period.

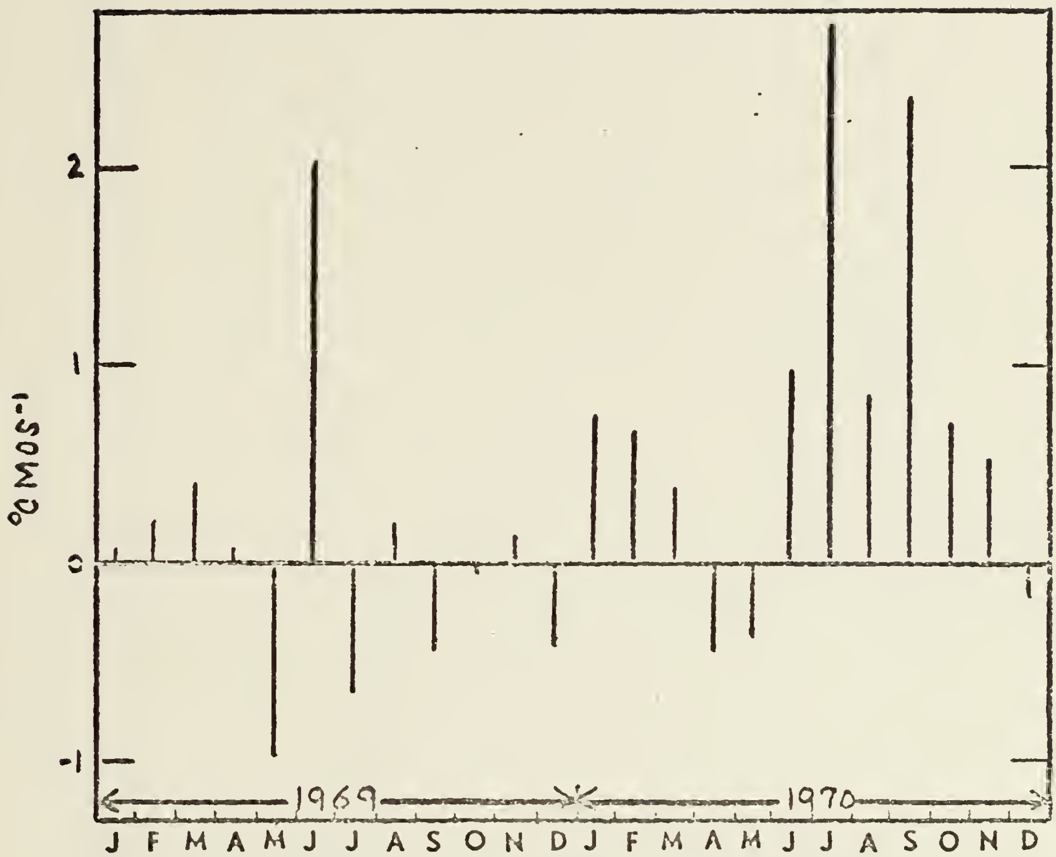

Figure A6c: Monthly mean anomaly in SST change attributed to horizontal advection. Positive values indicate a period when colder advection is greater than the long-term mean for this period.

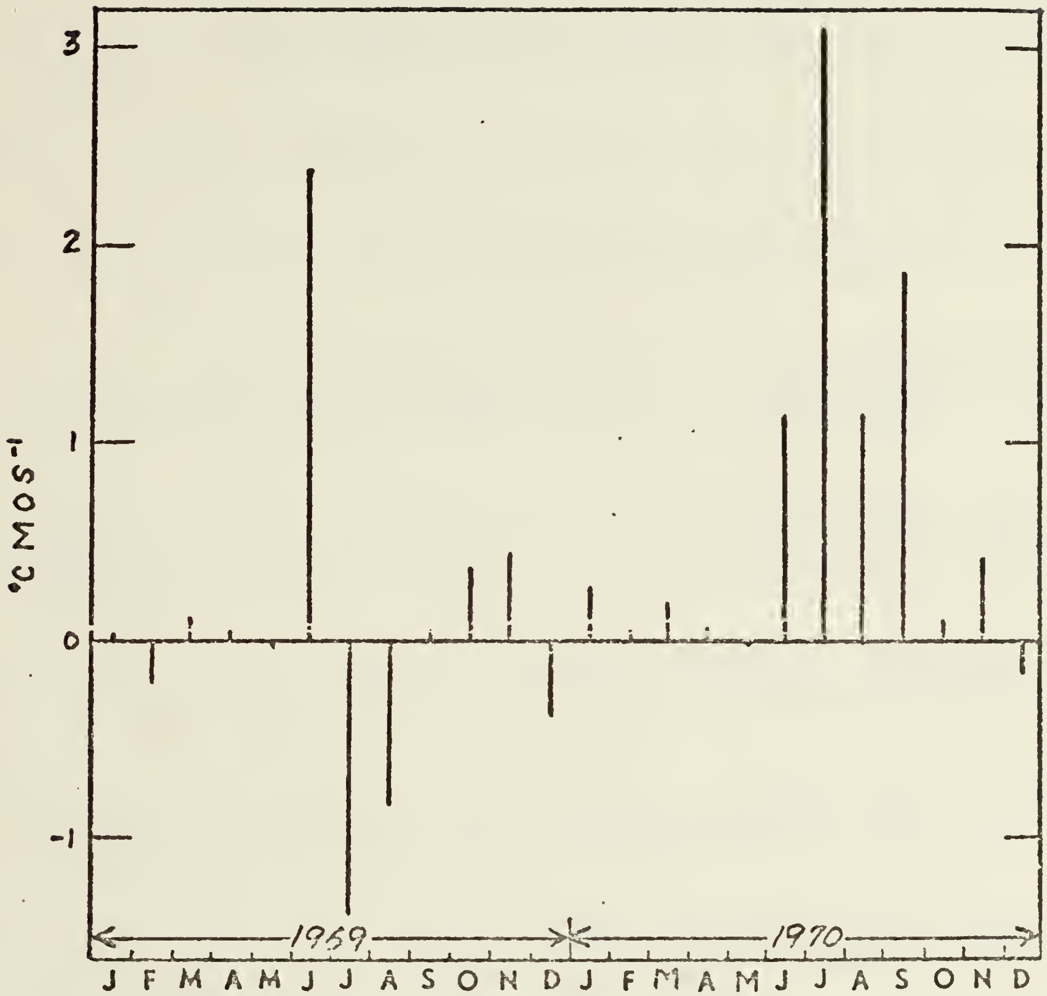

Figure A6d: Monthly mean anomaly in SST change attributed to heat exchange at the sea surface. Positive values indicate periods where the sea surface receives more heat from the atmosphere than normally expected for this period.

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